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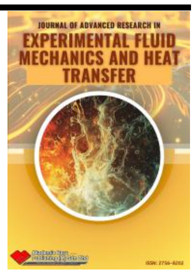

Adsorption of Nickel as Waste Contaminant using Nano-Sustainable-Based Particle Material: From a Bibliometric Perspective

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ABSTRACT

Adsorption is a crucial area, particularly in material technology and environmental management. A literature evaluation, bibliometric analysis, and visualization of scientific publications about the subject of adsorption from 2014-2024 are the objectives of this work. Using publication data from the Scopus database, which has gathered and retrieved 1,522 publications, a bibliometric analysis was carried out. This study examined several factors, such as (i) the year-over-year increase in research publications; (ii) the most cited articles; (iii) the most influential countries, journals, and institutions; (iv) the features of research documents; (v) productive research fields; and (vi) network and overlay visualization. The analysis's findings indicate that rising environmental consciousness around the world led to a notable rise in publications between 2021 and 2022. The most significant research uses eco-friendly nanoparticles for sustainable adsorption. While Chinese organizations like the Chinese Academy of Sciences and the Ministry of Education of the People's Republic of China dominate research contributions, motivated by local industry demands, the Journal of Colloid and Interface Science is the major journal in this field. The nations that have made the biggest contributions to research are China, India, and the United States. Chemistry, environmental science, chemical engineering, and materials science comprise the majority of the publications (83.3%). Three primary groupings are depicted in the topic visualization: particles, sustainability, and removal. The latest research trends include studies on the removal of organic and inorganic pollutants, sustainability, adsorption cycles, material reuse, and the development of new adsorbents. This study provides a systematic and objective view of research trends related to adsorption, which is expected to be a reference for researchers and practitioners to understand the development and future direction of research in this field.

1. Introduction

Wastewater treatment is a significant concern in Indonesia, given the high degree of industrialization, which contributes to an increase in the amount of liquid wastewater produced [1-3]. One of the sources of pollution is the vast amount of wastewater that is simply thrown into water

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bodies without first being processed, or that has been handled but does not meet the requirements [4,5]. This occurs because simple and efficient wastewater treatment technology has not been optimally deployed, particularly in industry [6]. Waste contamination causes major environmental damage. If the contaminant content (such as heavy metals, dyes, and organic compounds) exceeds the threshold and has highly hazardous qualities, it accumulates in the body and can cause major health problems [6,7]. Several methods for removing pollutants are now being investigated, including ion exchange, filtration, electrochemistry, solvent extraction, phytoremediation, and adsorption. However, various constraints limit the use of water treatment processes, including expense, proper disposal, and safety concerns [8,9].

Adsorption is the most effective of these strategies because it is less expensive, environmentally beneficial, and simple to implement. Adsorption is a physical or chemical process by which ions, molecules, or particles cling to the surface of an absorbent material. This approach offers several advantages, including the capacity to remove a wide range of pollutants, such as heavy metals, organic chemicals, and other hazardous compounds. Furthermore, adsorption technology is generally easy to deploy, has minimal operational costs, and may be employed at different scales. [10-20]. In Indonesia, waste processing through the adsorption process is still evolving, as evidenced by the development of exploratory studies on various adsorbents such as adsorbents based on natural materials (such as biomass), carbon, and metals to improve the efficiency and effectiveness of the adsorption process [10-20]. Aside from that, innovation in adsorption technology comprises surface modification of adsorbents and the development of novel materials with high adsorption capacity.

Although extensive study has been conducted in this sector, the knowledge and use of adsorption technology in many industries and on a worldwide scale, particularly in Indonesia, has yet to be explored. Furthermore, the research gap in this study presents vital insights regarding the effectiveness and scientific progress of Sustainable Material nano-based adsorbents as heavy metal (especially nickel) adsorbents, whose focus are (i) examination of various adsorption mechanisms, including observation of their characteristics from various sources, with a focus on their efficiency in adsorbing various heavy metals; (ii) analysis of the increasing research interest in the field of nanomaterials, especially those derived from sustainable materials as adsorbent materials, with a tracker of the number of documents published each year; (iii) study of the contributions made by various countries and institutions to this research; (iv) identification of the most productive journals publishing articles on adsorption using sustainable material nano-based adsorbents; (v) determining the kin As a result, doing a bibliometric study is critical for assessing research trends, technical breakthroughs, and innovation orientations in this sector.

As a result, it is critical to conduct a bibliometric study to assess research trends, technical breakthroughs, and innovation orientations in this area. As a result, this study intends to emphasize the significance of using adsorption in wastewater treatment by assessing the worldwide research landscape, publication output patterns, nation participation, author collaboration, and study area distribution. The objective is that this will be a good method of studying collections of literature in certain subjects, such as journals, which can be beneficial in academic settings.

2. Literature Review

2.1 Engineered Sustainable Nanoparticle Preparation

The field of environmental remediation, including aquatic environments, is increasingly focused on nanoparticles. A "Nano," derived from the Greek word "Nanos," meaning tiny, refers to a very small size of one per one billionth of a meter (1×10-9 meter). Nanoparticles (NPs) in nanomaterials typically range in size from one to one hundred nanometers. NPs can exist in a range of material phases, including gasses, liquids, and solids. Because of their unique properties, nanoparticles are extremely appealing and relevant for applications in a wide range of scientific and technological disciplines. Nanoparticles can be divided into several groups based on their properties and composition (as illustrated in Figure 1). Catalysis and sensors, for example, typically employ inorganic nanoparticles such as metals or metal oxides. Polymer nanoparticles can be used in a variety of medicinal applications, including drug delivery. Other nanomaterials include solid lipids, liposomes, nanocrystals, nanotubes, and dendrimers; all have benefits in several applications, including renewable energy and pharmaceuticals [21].

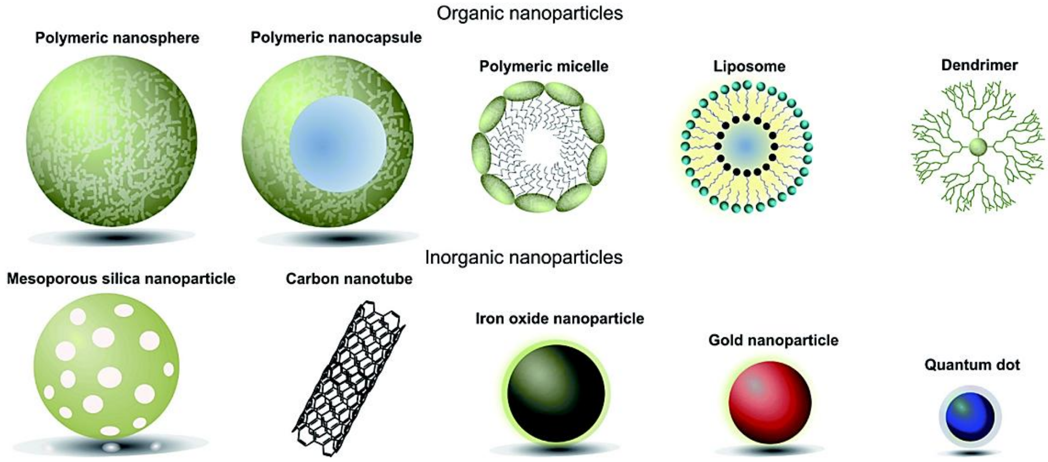

Fig. 1. Different types of nanomaterials

In general, there are two approaches to nanoparticle synthesis, namely bottom-up and top-down approaches as illustrated in Figure 2. The bottom-up synthesis method, also known as the physicochemical method (as illustrated in Figure 3), is the process of building materials from small particles such as atoms or molecules where the methods include using particles in gaseous or aerosol form (aerosolization), involving the deposition of a thin layer of material on a surface by vaporizing a chemical precursor and evaporating it (chemical vapor deposition), forming atomic layers in a controlled manner through molecular deposition under high vacuum (molecular beam epitaxy), and others. Top-down approaches (as illustrated in Figure 3) involve cutting or shaping materials from larger structures to nano-size where these methods often produce waste or toxic by-products such as chemical etching (using chemicals to ablate materials to nano-size) and laser ablation (utilizing high-energy lasers to remove materials from surfaces) [22].

Green chemistry-based phytosynthesis improves human health and well-being while enabling a more environmentally friendly remedial nanoparticle production method [23]. In general, combining nanoparticle bio/photosynthesis processes with technologies such as phytoremediation and phytomining can open up new paths for the application of phytotechnology [24]. Vascular plants, microalgae, fungi, bacteria, and their extracts are some of the biological agents that can be used in the nanoparticle photosynthesis process [25]. Plants use molecular tolerance mechanisms and metabolomics methods to promote nanoparticle production. In this situation, plant extracts contain biomolecules such as proteins, enzymes, polysaccharides, amino acids, vitamins, secondary metabolites, photosynthetic pigments, and others that function as reducing agents [23]. With the advancement of nanoparticle biosynthesis technology, this invention has the potential to become a sustainable nanofactory. As a result, plant-based nanoparticles have significant potential to alter different domains such as the environment, biomedicine, bioenergy, agriculture, food security, and resilience [24].

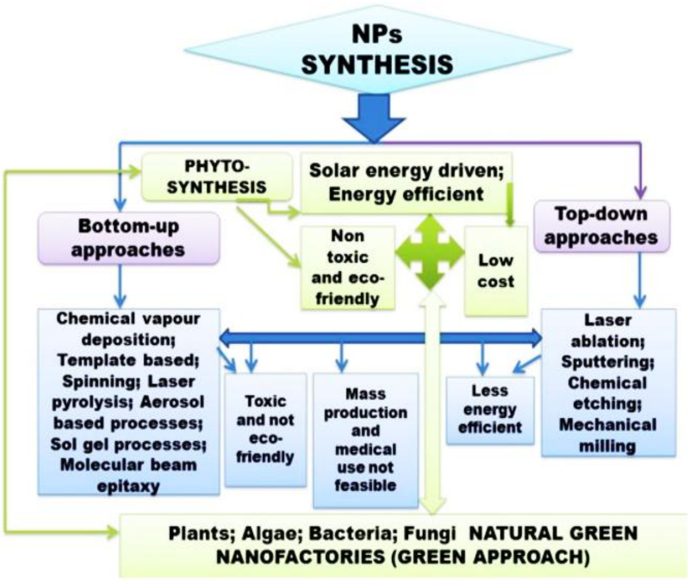

Fig. 2. Two common approaches in nanoparticle synthesis

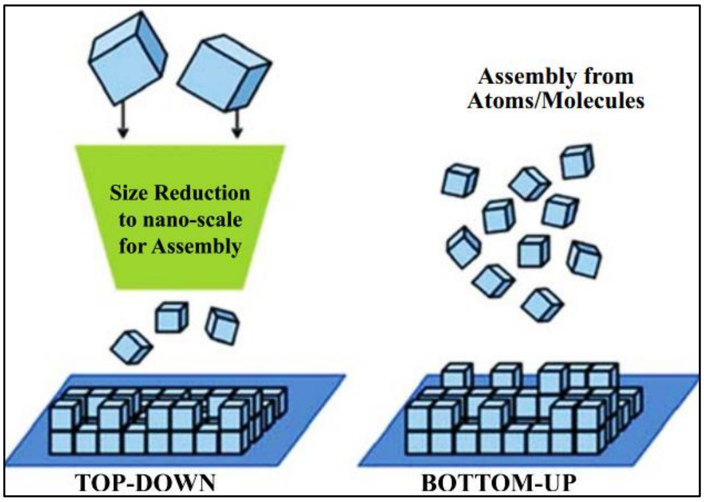

Fig. 3. Illustration of bottom-up and top-down approaches

2.2 Nano-Sustainable-Based Particle Material for Adsorbent Preparation

Numerous materials have been researched to remove water contaminants, largely through physical mechanisms such as adsorption, which is one of the most popular and effective ways of water treatment. Because of its exceptional ability to absorb a wide spectrum of pollutants, both organic and inorganic, activated carbon is the most widely used adsorbent material [26,27]. Although activated carbon is extremely successful, there are still many difficulties to overcome, especially when employing it commercially. One of the key barriers is the high cost of producing activated carbon, which entails stages such as carbonization and activation at high temperatures and typically requires significant energy and, in some cases, expensive raw materials. Because of these challenges, its use is less cost-effective for large-scale applications, especially in places with limited resources. Furthermore, the question of activated carbon regeneration and disposal at the end of its useful life raises serious environmental concerns. Regenerating activated carbon is often a costly chemical or thermal technique that may result in additional waste. Disposing of activated carbon after it is no longer useful may cause extra problems, especially if the substance has absorbed hazardous pollutants. Therefore, although activated carbon has many advantages, alternatives or innovations are needed to overcome these limitations, such as the use of nano-based materials that are more environmentally friendly and economical.

The benefits of adsorption techniques for pollution removal, combined with the inherent limits of conventional adsorbents, have prompted research into more ecologically acceptable and sustainable alternatives [28]. These alternatives are sometimes referred to as sustainable adsorbents, and they are typically created from natural materials. These materials are popular due to their widespread availability, particularly in agrarian nations, as well as their economic, environmentally benign, biodegradable, and low-cost features [29]. Abundant natural resources, such as agricultural waste, are becoming a primary focus in the development of sustainable adsorbents. Crop residues, fruit peels, rice husks, bagasse, and other organic wastes are frequently discarded without being properly utilized. Utilizing these wastes not only creates a solution for the purification of home and industrial waste streams but also achieves the goal of more responsible waste management [30].

These sustainable adsorbents are categorized into numerous types based on the properties of their source materials, modification procedures, and adsorption mechanisms. Each category has advantages and disadvantages, but all have significant opportunities to minimize reliance on traditional adsorbents such as activated carbon, which are frequently expensive and difficult to recycle. By constantly developing and analyzing these materials, sustainable adsorbent-based systems are projected to deliver more cheap, efficient, and environmentally friendly solutions to global waste management.

2.2.1 Agricultural waste-based biosorbent

Crop residues, organic waste, and byproducts of agriculture-based industries are all excellent candidates for the creation of sustainable adsorbents [31]. These materials are lignocellulosic, which means they are made up of three primary components: lignin, hemicellulose, and cellulose [32,33]. These three components produce a complex structure with active functional groups such as hydroxyl (-OH), carbonyl (C=O), ether (-C-O-C), and methoxyl ($-OCH_3$). These functional groups allow for chemical interactions with numerous sorts of contaminants, making them ideal materials for adsorption technology. Adsorbents based on agricultural materials can be used through three basic techniques, including [27,34]:

i. In raw form: The material is used directly without modification, utilizing the natural characteristics of lignocellulose and its active groups.
ii. As a modified waste material: The material undergoes physical or chemical modifications to improve its adsorption capability, such as adding more active groups or increasing porosity.
iii. In the form of activated carbon: Agricultural materials are processed through carbonization and activation to create an optimal microporous structure, which is highly effective in absorbing organic and inorganic pollutants.

Crop residues and organic waste are examples of agricultural products that have a high carbon content but minimal ash and other inorganic components, making them ideal for use as a foundation material for the synthesis of activated carbon. Activated carbon is created by thermally processing charcoal, which is then activated by physical, chemical, or a combination of the two procedures [35]. Furthermore, adsorbents based on agricultural materials can be altered by several techniques, including oxidation, polymerization, and acid or basic treatment, to increase their adsorption capability [36]. The use of mustard plant ash to remove the herbicide 2,4-D from water is an excellent example of agricultural waste as an adsorbent. This ash is dried, incinerated, and oven-dried, yielding essential elements like calcium oxide, potassium oxide, and phosphorus pentoxide, all of which are helpful soil micronutrients.

Subsequently, herbicide clearance in this study was greater than 90% at pH 2-4, indicating outstanding performance in environmental applications [37]. Furthermore, rice husk ash has been shown to effectively remove the herbicide 4-chloro-2-methylphenoxyacetic acid from aqueous solutions. With a maximum adsorption capacity at low temperatures (1.681 mg/g at 303 K), the adsorption process was exothermic. However, as the temperature rose, the capacity dropped due to the decreasing affinity of rice husk ash for herbicides. Overall, these materials are not only effective as eco-friendly adsorbents, but they also serve as soil fertilizer, making them a long-term, multifunctional solution to waste management and environmental contamination [38].

2.2.2 Biosorbent based on natural inorganic materials

Natural inorganic materials such as clays and zeolites are commonly used as adsorbents due to their abundance, low cost, and suitable qualities for absorbing contaminants [39]. Clays, for example, have hydrophilic properties and a negative charge that allows them to absorb insecticides with a positive charge. However, the ionic strength of the solution and pH levels have a considerable impact on the efficacy of this adsorption method. Because the clay surface and carbaryl have larger interaction forces, studies show that using untreated clays from Agadir, Morocco, to remove pesticide carbaryl is more effective at low pH (pH 3). However, the significant cost of decreasing the pH of the solution restricts the widespread use of clays. Clays are commonly chemically modified to improve their adsorption capacity [40]. For example, as compared to unmodified clays, bentonite, and montmorillonite modified with organic compounds such as octadecyl amine (ODA-M) or in conjunction with aminopropyl triethoxysilane (ODAAPS-M) showed improved pesticide adsorption capacities. With efficiencies ranging from 59 to 82%, these modified adsorbents outperformed the original clays, which only removed 47-66% of pesticides.

According to [41], this study found that the optimal clay dosage for pesticide removal is around 40 mg/L. As a result, materials such as clays and zeolites—particularly modified ones—provide effective wastewater treatment options, but cost and regeneration remain major concerns. Zeolites are crystalline aluminosilicate minerals with a microporous network, similar to clays, that make them particularly useful for a range of applications, including pollutant removal from water [42,43]. These materials can be found naturally or synthesized, and have the advantages of a huge surface area and very small pores (0.1-1 nm). Zeolites may effectively collect microorganic molecules via adsorption mechanisms due to their small pore size and unique structure [44]. One of the primary qualities that makes zeolites so helpful is their hydrophobicity, which is determined by the amount of aluminum in their aluminosilicate framework. The Hydrophobicity Index (HI) measures zeolites' propensity to attract organic molecules rather than water. This characteristic makes zeolites very effective at removing small organic pollutants from wastewater. Zeolites, with their microporous structure, huge surface area, and hydrophobic qualities, are an efficient and trustworthy material choice for wastewater treatment and environmental protection [45].

2.2.3 Biosorbent

Biological adsorbents are composed of biological components such as bacteria, algae, fungi, and yeast. These materials can remove contaminants through chemical and physical sorption methods [46]. The key benefits of these adsorbents are their widespread availability, low manufacturing costs, high performance in pollutant elimination, and selectivity. Biological adsorbents may absorb both dead and living material. Despite its efficacy in removing dangerous organic debris, living biomass has limitations, including vulnerability to pollutant toxicity and the need for a feeding source to sustain the organism. Dead biomass, on the other hand, is more helpful because it requires no special care and may be stored at room temperature for long periods without spoiling. Dead biomass is also an inexpensive and environmentally friendly waste treatment solution because it can be recycled and reused, similar to the benefits of traditional adsorbents [47]. Adsorption experiments have shown that biomass from various sources can be used to remove insecticides.

Several studies have demonstrated the bioremediation capacity of bacterial, fungal, and microalgal biomass. A study using the microalgae Scenedesmus obliquus and Anabaena sphaerica, for example, found that a dosage of 1 g/L microalgae could neutralize up to 80% of the pesticide diuron in 80 minutes at a starting concentration of 40 mg/L at pH 3. A. sphaerica surpassed S. obliquus due to its larger surface area (52.2 m^2/g) compared to the smaller surface area (25.8 m^2/g) [48]. Table 1 provides a summary of isotherm models for sustainable adsorbents based on agricultural waste.

Table 1
Summary of isotherm models of various sustainable adsorbents

No.	Adsorbent	Target	Isotherm model	References
1	Pomegranate peel powder	Oxamyl	Freundlich	[49]
2	Banana peel powder	Oxamyl	Freundlich	[49]
3	Activated carbon derived from coconut shell	Hexachlorocyclohaxane	Freundlich	[50]
4	Activated carbon derived from date stones	2,4-Dichlorophenoxyacetic acid	Langmuir	[51]
5	Biochar from banana peel	Atrazine	Langmuir	[52]
6	Activated carbon from the Langsat empty fruit bunch	2,4-Dichlorophenoxyacetic acid	Langmuir	[53]
7	Activated biochar oil palm fiber	Ethylparaben	Langmuir	[54]
8	Watermelon peel powder	Methyl parathion	Langmuir	[55]
9	Oat ash	Tetrachloroethylene	Freundlich	[56]
10	Wheat ash	Tetrachloroethylene	Freundlich	[56]
11	Activated carbon-derived banana stalk	2,4-Dichlorophenoxyacetic acid	Freundlich	[57]
		Bentazon	Freundlich	[57]
12	Walnut shell powder	Carbofuran	Freundlich	[58]
		Chloropyriphos	Freundlich	[58]
13	White bentonite clay	Metalaxyl	Freundlich	[59]
14	Ghassoul clay	Tricyclazole	Freundlich	[59]
15	Mustard plant ash	2,4-Dichlorophenoxyacetic acid	Freundlich	[60]
16	Apple peel powder	2,4-Dichlorophenoxy butyric acid	Langmuir	[61]
17	Orange peel powder	2,4-Dichlorophenoxy butyric acid	Langmuir	[61]
18	Biochar from corn cob	Atrazine	Freundlich	[62]
19	Biochar from rice husk	Atrazine	Freundlich	[62]
20	Biochar from bamboo chips	Atrazine	Freundlich	[62]
21	Sunflower seed shell powder	Alachlor	Freundlich	[63]
22	Chestnut shell powder	Imidacloprid	Freundlich	[64]
23	Peanut shell powder	Endosulfan	Freundlich	[65]
24	Avocado stones powder	Endosulfan	Freundlich	[65]

2.3 Mechanism of Adsorption

The physical and chemical interactions between one material (sorbate) and the surface or internal structure of another (sorbent) are known as "sorption" processes. This process involves two processes: adsorption, in which sorbate molecules stick to the sorbent surface, and sorption, in which the sorbate penetrates the sorbent structure. Depending on the material and process conditions, these two mechanisms frequently occur concurrently or separately. To better characterize this process, the terms "sorbent" and "sorbate" are used to refer to the material that conducts sorption, the substance that is adsorbed or absorbed, and the substance that may undergo sorption, respectively [66].

Adsorption is a process in which molecules or particles (adsorbate) adhere to the surface of another material (adsorbent). This process is regulated by the adsorbent's surface properties, such as pore size and surface area. Adsorption happens when the attraction between the adsorbent surface and the adsorbate exceeds the adsorbate's internal energy. For example, glue can attract and hold particles to specific surfaces [67,68]. Adsorption is classified into two types based on the forces involved: physisorption, which is caused by weak intermolecular forces such as London-van der Waals forces that are usually not permanent and can be easily reversed, and chemisorption, which involves the formation of stronger chemical bonds between the adsorbate and adsorbent. Because chemical reactions are involved, chemisorption is more persistent and difficult to reverse [69].

Adsorption takes place at the interface layer between the gas or liquid (adsorbate) and the solid material's surface (adsorbent). This interfacial layer is made up of two parts: a gas or liquid part that is in the material's force field, and a solid layer that attracts adsorbate particles. This process is directly opposed to desorption, in which previously attached particles are liberated into their original phase. In some situations, a hysteresis phenomenon occurs, that is, a change in the route between adsorption and desorption, which results in a hysteresis circle on the adsorption isotherm graph. These circles are commonly found in materials having mesoporous structures, which are good for adsorbing particles due to their porous size. The substance in its pre-adsorption form is referred to as adsorptive, and the material after adsorption is adsorbate. Assimilation occurs when adsorbate particles adhere to the surface while also permeating deeper into the solid substance. Figure 4 depicts the main language used in adsorption methods to remove harmful pollutants from the environment [70].

Figure 5 depicts the many sorts of interactions that occur during the adsorption process between the adsorbent (absorbing material) and the adsorbate (absorbed substance). This phenomenon is governed by different types of interactions including hydrophobic interactions, van der Waals forces, electrostatic interactions, π-π stacking, and hydrogen bonding between adsorbent and adsorbate. These interactions are critical in determining how well an adsorbate can adhere to the adsorbent surface. These types of interactions include [40,71,72]:

i. Hydrophobic interaction: This occurs when the adsorbent and adsorbate tend to repel water, thus attracting each other. This interaction is common in non-polar molecules.
ii. Van der Waals force: This is a weak attractive force that occurs due to fluctuations in electron distribution on molecules, allowing adsorbate molecules to attach to the adsorbent surface.
iii. Electrostatic interaction: Occurs between positive and negative charges on the adsorbent and adsorbate, such as ions in solution.
iv. Hydrogen bonding: Occurs when a hydrogen atom bound to an electronegative atom such as oxygen or nitrogen forms an interaction with a free electron pair from another atom.

v. π-π interaction: Occurs between molecules that have aromatic rings or π-electron structures, such as certain organic compounds, which interact with each other through a stack of π orbitals.

Depending on the adsorbent and adsorbate's chemical and physical properties, one or more of these interactions may occur at the same time during the adsorption process. These interactions work together to determine a system's efficiency, selectivity, and adsorption capacity. Understanding these mechanisms allows for the design or modification of adsorbents to increase their performance in specific applications like waste treatment or chemical purification [40]. Because the adsorbent and adsorbate are water-repellent (hydrophobic), they are attracted to one another via a process known as hydrophobic interaction. This interaction is particularly effective for removing organic pollutants such as ethinylestradiol and bisphenol-A when carbon nanotubes are used [72].

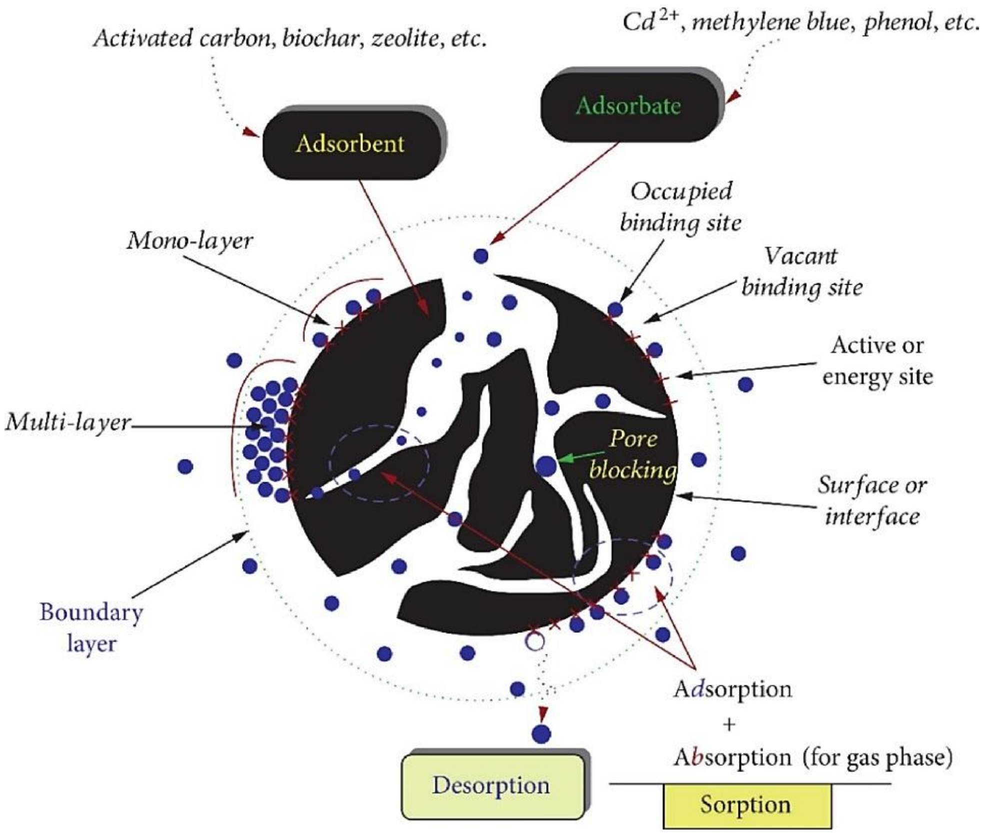

Fig. 4. Basic terminology used in the adsorption process

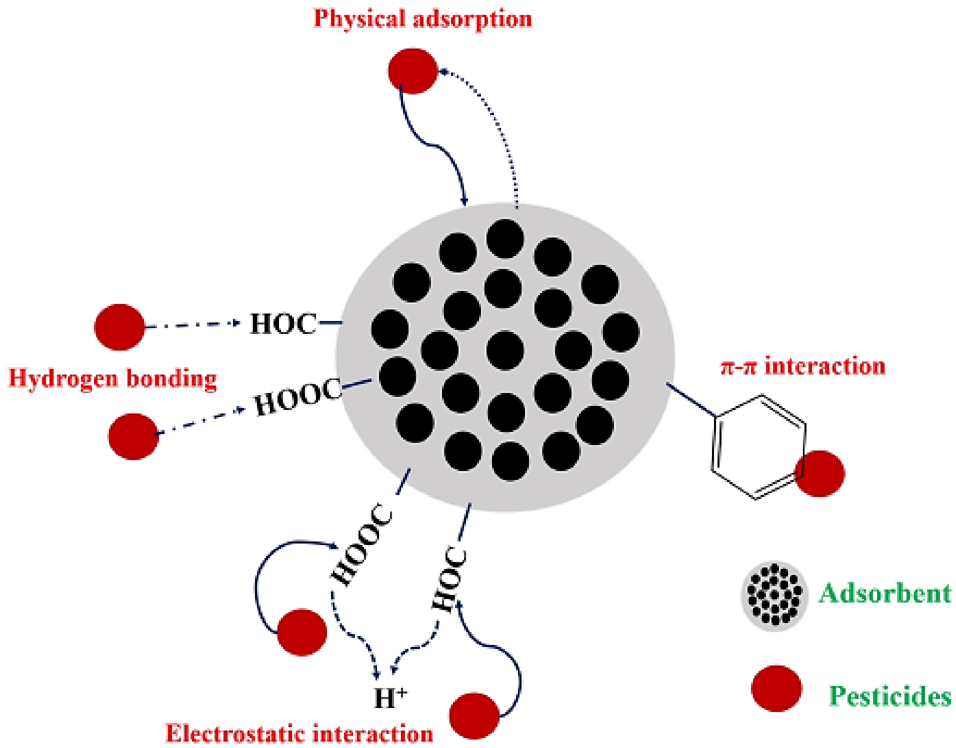

Fig. 5. Various interaction mechanisms are involved in pesticide removal through adsorption

The properties of the pollutant and adsorbent, particularly the material's surface area, influence how well the hydrophobic interaction works. Researchers discovered that the adsorbent's surface area has a considerable impact on how successfully some contaminants are absorbed [73]. For example, perfluoro-2-propoxypropanoic acid (GenX) was adsorbed onto activated carbon by hydrophobic interactions. This contact also helps to minimize the electrostatic repulsion that often occurs between the negative charge of GenX and activated carbon [74]. Adsorption involves both hydrophobic and π-π interactions, particularly for substances with aromatic structures or molecules containing π electrons. These interactions are excellent at removing colors and organic pollutants from wastewater, according to research on wastewater treatment [40]. The combination of these interactions makes the adsorption process exceedingly adaptable and efficient in dealing with diverse types of contaminants.

Adsorbents can remove impurities such as colors, pharmaceuticals, and pesticides by utilizing functional groups such as O-H, N-H, and H-F. When these groups interact with hydrogen, electronegative elements such as oxygen, nitrogen, or fluorine can form hydrogen bonds, which attract and trap impurities. Hydrogen bonding can efficiently remove some pollutants from wastewater [72]. Furthermore, electrostatic interactions are important for adsorption, especially when the adsorbent and adsorbate are charged. Adsorbents, for example, can be modified to generate charge via oxygen groups by adding hydroxyl (-OH) or amine (-NH_2) groups. These alterations improve the adsorbent's potential to absorb a range of organic pollutants, such as dyes, pesticides, and aromatic compounds, which are commonly present in wastewater [40].

Van der Waals forces, which are weak interactions between molecules, also contribute to pollution retention. However, these pressures are less steady and easily released. Van der Waals forces are frequently used with hydrogen bonding to improve the efficiency of the removal procedure for particular contaminants, such as phenol [72]. By combining these methods, adsorbents can be changed to remove various types of contaminants from the environment more efficiently.

Some of the variables that affect the process of eliminating pollutants from water include the interaction between the adsorbent material and the adsorbed substance (adsorbate), the adsorbent's surface area, the adsorbent-to-adsorbate ratio, the adsorbent's particle size, temperature, pH, and the length of contact time (see Figure 6). The combined influence of these components dictates the efficiency with which pollutants are removed. By understanding and optimizing these factors, the process of removing contaminants, including colors, from wastewater can be carried out more effectively, even on an industrial scale [40]. The adsorption process is influenced by several major aspects relating to the nature of the adsorbent and pollutant, as well as the system conditions, including [75,76] aspects below.

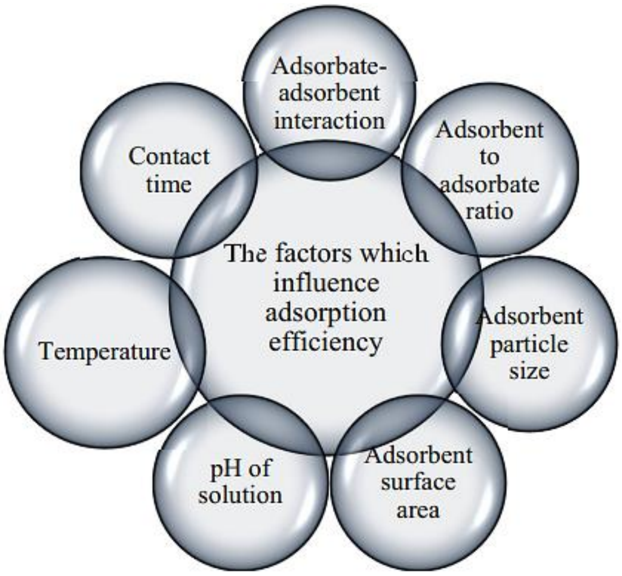

Fig. 6. Factors affecting adsorption efficiency in the adsorption process

2.3.1 Adsorbent functional group

The functional groups (such as hydroxyl, carbonyl, and C-O groups) on the adsorbent surface play an important role in determining the mechanism of interaction with pollutants as follows [75]:

i. The adsorption mechanism of heavy metal ions is dominated by chemosorption processes which include: (i) complexation (metal ions form strong chemical bonds with organic groups of functional groups on the adsorbent surface); (ii) precipitation (metal ions react with hydroxyl or mineral groups on the adsorbent to form insoluble precipitates); (iii) π-π interactions (this interaction mainly occurs in compounds with aromatic groups).
ii. A variety of adsorption processes, including a mix of physisorption and chemisorption, are involved in the adsorption mechanism of organic compounds (such as dyes). Weak interactions, such as hydrogen interactions, van der Waals forces, or electrostatic forces, are what define physisorption adsorption. For instance, if the dye contains groups like hydroxyl (-OH) or carbonyl (C=O) that can link with polar groups on the adsorbent, hydrogen bonding will take place. Stronger interactions involving the creation of chemical bonds between the dye and its functional groups—typically in the form of π-π interactions—are what define chemisorption adsorption. These π-π interactions occur when the dye has π electrons (e.g., from an aromatic ring), which interact with aromatic groups on the adsorbent that also have delocalized π electrons.

iii. Adsorption mechanisms that combine physisorption and chemisorption interactions often occur in the case of dye adsorption. For example, negatively charged dyes can adhere to positively charged biochar through electrostatic interactions (physisorption). At the same time, dye molecules can form chemical bonds with functional groups on the biochar through π-π interactions or hydrogen bonding (chemisorption).

2.3.2 Adsorbate characteristics

The nature and qualities of adsorbents have a considerable impact on how they absorb contaminants. For example, biochar and heavy metal ions such as Pb(II), Cu(II), and Zn(II) typically interact via chemisorption. This process comprises actions such as ion exchange, which occurs when metal ions replace mineral ions on the surface of biochar, as well as the formation of chemical compounds with functional groups on biochar. In contrast, physisorption—that is, weaker physical connections such as electrostatic, hydrogen, or hydrophobic interactions—is commonly utilized to adsorb organic compounds like dyes and medicines. The chemical composition of contaminants, such as their molecular size, solubility, and electrical properties, is an important part of this mechanism. For example, molecules with high polarity (more soluble in water) tend to interact with polar functional groups on biochar, while less polar molecules will rely more on hydrophobic interactions with the biochar surface [75].

2.3.3 pH system

The pH of the solution influences the nature of the charge on the surface of the adsorbent and pollutant. At low pH, for example, positively charged adsorbents can adsorb anions such as negatively charged chemical molecules. At high pH, negatively charged adsorbents can adsorb cations such as heavy metal ions. pH also impacts mechanisms such as precipitate formation or ion exchange for metal ions at high pH, whereas organic compounds tend to interact by electrostatic attraction at low pH [75].

2.3.4 Adsorbent pore structure

The pore structure of an adsorbent is one aspect that influences adsorption effectiveness since it impacts the adsorbent's ability to retain contaminants. Adsorbents have various types of pores based on their size and function, including: (i) micro pores that provide a large surface area for the interaction of small molecules such as metal ions; (ii) meso and macro pores aid in the transport of large molecules such as dyes into the adsorbent; and (iii) the inter-pore connectivity structure is critical to enhance the diffusion of pollutants throughout the adsorbent surface area [75].

2.3.5 Mineral content on adsorbent

Depending on the biomass source, biomass-based adsorbents using oxygen-minimizing processes contain a variety of minerals such as calcium, magnesium, potassium, and others. In the ion exchange process, minerals in the adsorbent act as ion donors. This mechanism occurs when mineral ions in the adsorbent, such as Ca^{2+}, Mg^{2+}, or K^{2+}, are replaced by pollutant ions from solution, such as heavy metals (like Pb^{2+} and Cd^{2+}) or other inorganic ions. This technique increases biochar's ability to absorb contaminants, making it more useful as an environmental restoration material. According other literature [75], the minerals in the adsorbent can also react with heavy metal ions in solution to form less soluble molecules that reduce the concentrations of heavy metals in the aquatic environment.

2.3.6 Adsorbent modification method

Natural adsorbents frequently have limitations in adsorption efficiency; hence, physical and chemical changes are used to improve their adsorptive capabilities. The modifications attempt to enhance the surface area, number of active sites, and selectivity. Modification can be done in two ways: physically and chemically. Physical alteration includes heating to create additional micro and meso pores, as well as mechanical grinding to smooth the structure and reduce particle size, hence improving pollutant interaction. Chemical modification can be done through activation with acids and bases, impregnation of metals or metal oxides, and functionalization with organic compounds to add functional groups or embed new elements that can improve the attraction to certain contaminants [75].

2.3.7 System condition

Temperature, adsorbent mass, contact time, and initial concentration are all critical system characteristics that affect the adsorption process. Each component must be extensively investigated since it has a significant impact on the effectiveness and process of adsorption. The kinetics and thermodynamics of adsorption are strongly influenced by temperature. Because molecules have more kinetic energy at higher temperatures, pollutants such as chloramphenicol can quickly reach the adsorbent surface and interact with active sites. If the adsorption is endothermic, raising the temperature can improve its capacity. Exothermic processes, on the other hand, might be rendered ineffective due to desorption caused by excessive heat.

Furthermore, temperature affects the physicochemical features of the solution, such as viscosity, which influences the transport of molecules to the adsorbent. The adsorbent's total mass determines the number of active sites available for pollutant absorption. Pollutant removal efficiency tends to increase with adsorbent bulk because more active sites are available. Nonetheless, there exists an optimal limit. Particle agglomeration can occur when the adsorbent mass is extremely large, diminishing efficiency per unit mass and limiting active site accessibility. To maximize efficiency and reduce material waste, adsorbent dosage must be carefully set. Because the adsorption process is not instantaneous, contact duration is another important factor. Because there are many empty active sites at the beginning of the process, the adsorption speed is frequently high. However, as pollutants build in the active sites, the rate of adsorption slows until equilibrium is attained, when the number of molecules adsorbed and desorbed is equal.

The type of adsorbent, surface qualities, and environmental conditions all influence the optimum contact time. It must be properly regulated to avoid wasting time and energy, as extending the contact time after equilibrium is reached does not result in a notable increase in efficiency. The driving force for mass transfer from the solution to the adsorbent surface is affected by the initial concentration of pollutants. Higher initial concentrations promote faster mass transfer by increasing the concentration differential between the solution and the adsorbent surface. At very high concentrations, the adsorbent's adsorption capacity per unit mass increases, but the removal efficiency decreases because the adsorbent's active sites can quickly become saturated. To ensure an optimal adsorption process, it is critical to adjust the initial concentration and adsorbent dosage [76].

3. Methodology

The keywords used for this study were selected based on how well they addressed the primary goals of the investigation, which were to treat wastewater using adsorption, sustainability, and nanomaterials. A preliminary assessment of the literature guided the precise selection of keywords such as "adsorption," "nickel," "nanoparticles," "colloid," "sustainability," and "education," all of which were frequently associated with recent developments in adsorption technology. While "colloid" and "nanoparticles" reflected the growing interest in new materials for adsorption processes, "Nickel" was included due to its prevalence as a pollutant in industrial effluent. "Education" was added to identify bibliometric trends in scholarly contributions and knowledge dissemination, while "Sustainability" aligned with the global emphasis on environmentally friendly technologies. Scopus-indexed papers from 2014 to 2024 were incorporated into the inclusion criteria to ensure the relevance and quality of the data. The analysis considered both review articles and research publications.

Review articles were valued for summarizing trends, highlighting challenges, and suggesting future research directions, whereas research publications were assessed for their unique contributions to adsorption technology. Publications with a minimum citation threshold were prioritized in specific analyses to emphasize significant contributions. To maintain accuracy and consistency in the analysis, exclusion criteria were established. Since the Scopus database predominantly indexes English-language publications, articles written in other languages were excluded to avoid inconsistencies in language-based interpretation. Similarly, publications without a clear year of publication were excluded to ensure the precision of temporal trend analysis. Publications unrelated to environmental applications or adsorption processes were also omitted from the dataset. By adhering to these standards, the study aimed to provide a comprehensive and targeted bibliometric analysis that supported the objectives of evaluating adsorption technology research trends, technological advancements, and knowledge gaps. Further details on data analysis and visualization using VOSviewer software are available elsewhere [77,78].

4. Results and Discussion

4.1 Research Growth

Figure 7 is the trend of adsorption research over the last five years (from 2019 to 2024). Research productivity in this field occurred in 2020, 2022, and 2023 with the number of documents at that time being 151, 176, and 181 documents, respectively. Meanwhile, in 2019, 2021, and 2024, the number of publication documents in this field was no more than 145 documents. The year 2022 was the most productive year with a significant increase in research in this field. In 2020, research on this topic increased as a result of the COVID-19 pandemic, which prompted many new studies on air and water research, including the development of adsorption technology to filter viruses, pollutants, and hazardous chemicals, increasing the focus on this research. During the recovery period of the COVID-19 pandemic (2022), research on this topic has decreased as many countries may start and refocus on pending research projects.

An increase in research in this area also occurred in 2023, which is the year when public interest in increasing environmental awareness increased due to important agreements such as the "Freshwater Challenge," which aims to protect and revive rivers and wetlands around the world. Therefore, in 2023, there is an increase in adsorption research due to the strong push towards green technology and efforts to tackle climate change. In 2024, there is a decline in research in this area due to a possible shift in research focus as some of the key objectives in adsorption technology development have been achieved during the previous period [10-20], thus reducing the urgency for further research in the short term. The trend demonstrates how adsorption research is dynamic and impacted by world events as well as changing environmental objectives. While the fall in 2024 might indicate a shift towards investigating other cutting-edge environmental science issues, the peak in 2022 highlights the significant emphasis on green technologies.

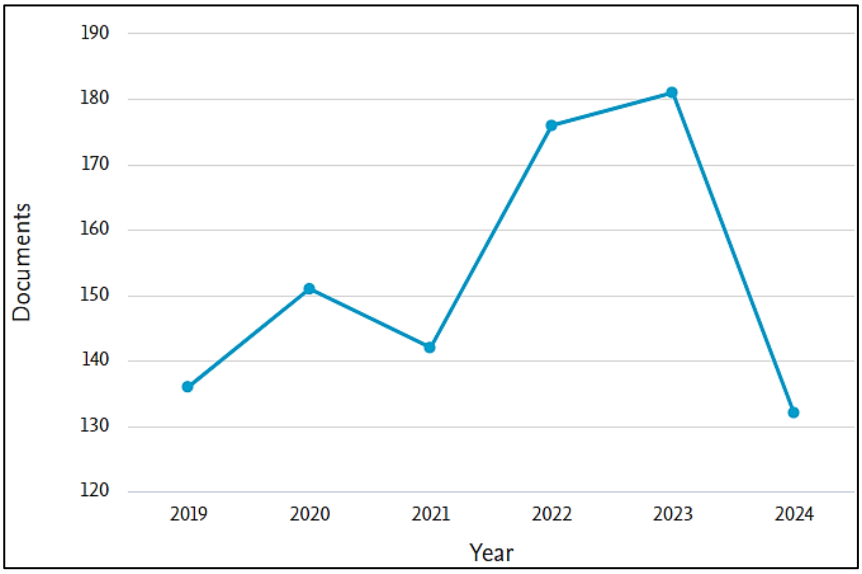

Fig. 7. Number of publications on the adsorption research on Scopus

4.2 The Basic Characteristics of the 10 Top-Cited Articles

Table 2 is lists of the 10 most cited article-type documents based on Scopus. The most cited research in this field highlights the characterization of sustainable adsorption processes by utilizing nano-sized, environmentally friendly adsorbent materials. These materials are often supramolecular-based and equipped with surface modifications to achieve optimal adsorption performance. Articles with the aforementioned characteristics are widely cited for several reasons, including:

i. Research focused on sustainable and environmentally friendly adsorption technologies is highly relevant to global efforts to address environmental issues such as water and air pollution. Environmentally friendly adsorbent materials offer safer and more sustainable solutions compared to conventional methods.
ii. The utilization of nanomaterials and supramolecules in adsorption is attracting great attention due to their unique properties that allow for increased adsorption efficiency and capacity. Nano-materials have a large surface area, while supramolecules enable specific and strong interactions with pollutants, increasing the effectiveness of the adsorption process.
iii. This research has broad potential applications in various industries, including water treatment, waste management, and clean energy production. This makes this research of great interest to academia, industry, and policymakers.

Table 2
Article in which the top 10 cited adsorption papers were published

No	Title	Authors	Citation	References
1	Power generation from ambient humidity using protein nanowires	Liu, Xiaomeng, Hongyan Gao, Joy E. Ward, Xiaorong Liu, Bing Yin, Tianda Fu, Jianhan Chen, Derek R. Lovley, and Jun Yao	428	[79]
2	Supramolecular Assembly-Induced Emission Enhancement for Efficient Mercury (II) Detection and Removal	Dai, Dihua, Zheng Li, Jie Yang, Chunyu Wang, Jia-Rui Wu, Yan Wang, Dongmei Zhang, and Ying-Wei Yang	308	[80]
3	Biochar-supported nanoscale zero-valent iron as an efficient catalyst for organic degradation in groundwater	Li, Zhe, Yuqing Sun, Yang Yang, Yitong Han, Tongshuai Wang, Jiawei Chen, and Daniel CW Tsang	292	[81]
4	Activated biochar derived from Opuntia ficus-indica for the efficient adsorption of malachite green dye, Cu+2 and Ni+2 from water	Choudhary, Manisha, Rahul Kumar, and Sudarsan Neogi	276	[82]
5	Emergence of complexity in hierarchically organized chiral particles	Jiang, Wenfeng, Zhi-bei Qu, Prashant Kumar, Drew Vecchio, Yuefei Wang, Yu Ma, Joong Hwan Bahng, Kalil Bernardino, Weverson R. Gomes, Felippe M. Colombari, Asdrubal Lozada-Blanco, Michael Veksler, Emanuele Marino, Alex Simon, Christopher Murray, Sérgio Ricardo Muniz, André F. de Moura, and Nicholas A. Kotov.	191	[83]
6	Use of chicken feather and eggshell to synthesize a novel magnetized activated carbon for sorption of heavy metal ions	Rahmani-Sani, Abolfazl, Pardeep Singh, Pankaj Raizada, Eder Claudio Lima, Ioannis Anastopoulos, Dimitrios A. Giannakoudakis, Selvaraju Sivamani, Tetiana A. Dontsova, and Ahmad Hosseini-Bandegharaei.	130	[84]
7	High-capacity Hg (II) and Pb (II) removal using MOF-based nanocomposite: Cooperative effects of pore functionalization and surface-charge modulation	Abdollahi, Nasrin, Sayed Ali Akbar Razavi, Ali Morsali, and Mao-Lin Hu.	129	[85]
8	Are nanoplastics able to bind significant number of metals? The lead example	Davranche, Mélanie, Cloé Veclin, Anne-Catherine Pierson-Wickmann, Hind El Hadri, Bruno Grassl, Laura Rowenczyk, Aline Dia, Alexandra Ter Halle, Florent Blancho, Stephanie Reynaud, and Julien Gigault.	128	[86]
9	Adsorption of diclofenac sodium on bilayer amino-functionalized cellulose nanocrystals/chitosan composite	Hu, Dalin, Ran Jiang, Nan Wang, Hongping Xu, Yang-Guang Wang, and Xiao-kun Ouyang	124	[87]
10	General synthesis of ultrafine metal oxide/reduced graphene oxide nanocomposites for ultrahigh-flux nanofiltration membrane	Zhang, Wanyu, Hai Xu, Fei Xie, Xiaohua Ma, Bo Niu, Mingqi Chen, Hongyu Zhang, Yayun Zhang, and Donghui Long.	119	[88]

4.3 The Basic Characteristics of the 10 Top-Cited Articles

Figure 8 shows five journal sources that are relevant to the scope of this research based on Scopus. The journals relevant to the research of this topic are Journal of Colloid and Interface Science, Chemosphere, Colloids and Surface A: Physicochemical and Engineering Aspects, Science of the Total Environment, and Journal of Hazard Materials, which have published 49, 45, 38, 32, and 24 documents, respectively. Journal of Hazardous Materials has a stable but relatively low publication trend compared to other journals, indicating that this journal remains consistent in publishing articles related to adsorption, even though the number is not too high. Journal of Colloids and Surface A: Physicochemical and Engineering Aspect shows a fairly fluctuating but significant publication trend, with a fairly large contribution in 2021 and 2022 before decreasing in 2023. Journal of Colloid and Interface Science shows relatively stable publications and does not show a significant spike, reflecting a consistent focus on collaborative research between surfaces and adsorption. Journal of Science of the Total Environment shows publications that tend to be stable from year to year, with a slight increase in 2022, indicating that this journal is a popular choice for research focusing on the environmental aspects of adsorption.

Journal of Chemosphere stands out as the journal with the highest publication spike in 2022, but experiences a sharp decline in 2023 and 2024, indicating a peak in attention given to adsorption-related research in those years, possibly due to globally relevant trends or topics. Overall, Chemosphere has a significant contribution in publishing adsorption research especially at the peak in 2022, followed by Science of the Total Environment, which offers a more stable trend. Fluctuations in the number of published papers reflect the variation in research focus as well as global priorities for the topic of adsorption in the context of environment and materials engineering. These journals play an important role in disseminating the latest and innovative research results in the field of characterization and application of sustainable adsorbent materials. They provide a platform for researchers to share their findings and contribute to the development of technologies that can effectively address environmental challenges. In detail, it can be seen that the featured areas of adsorption research topics are as follows:

i. Focuses on colloidal and surface interface research, including research on nano- and supramolecular adsorbent materials and surface modification to improve adsorption efficiency.
ii. Discusses the chemical environment, including studies on the removal of pollutants using sustainable and environmentally friendly adsorbent materials.
iii. Focuses on the physicochemical and engineering aspects of colloids and surfaces, with a focus on innovations in nano adsorbent materials and surface modification techniques.
iv. Focusing on holistic solutions to environmental problems, including the use of nanomaterials and supramolecules in adsorption processes for water treatment and waste management.
v. Exploration of hazardous materials and methods for their control and removal, including research on new adsorbent materials that are effective in removing hazardous pollutants from the environment.

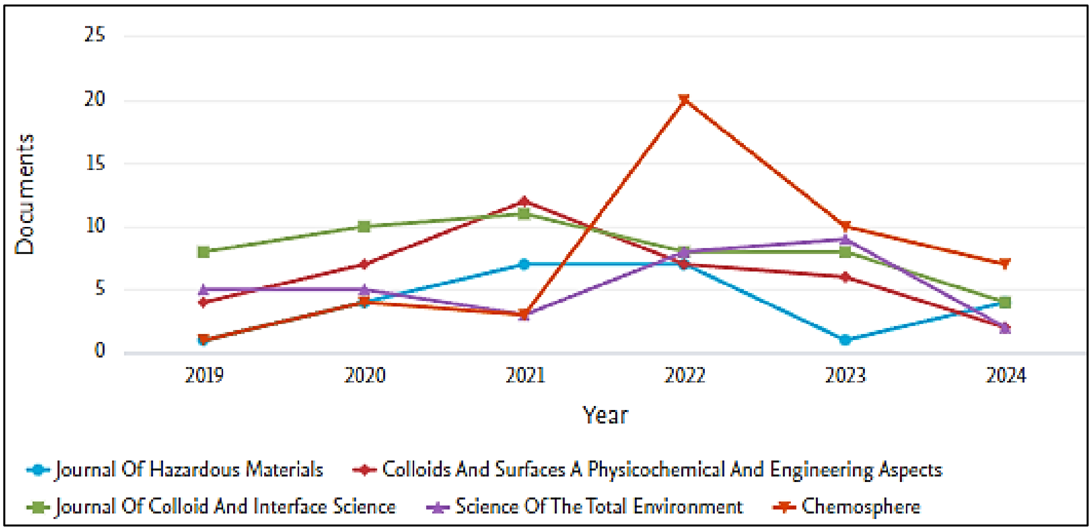

Fig. 8. Topmost influential journal in adsorption research

4.4 Leading Contributing Institutions

Figure 9 show the data for the ten most contributing universities in this study. The most contributing institution is the Ministry of Education of the People's Republic of China with 57 articles, followed by the Chinese Academy of Science with 38 articles, and the CNRS Center National de La Recherche with 21 articles. Then, seven other institutions have fewer than 20 articles. It is usually found that institutions affiliated with the highest contributing authors show the highest productivity. The two most productive institutions are from China because many industries in China require adsorption technology for various purposes, ranging from gas separation in the chemical industry to waste treatment in the manufacturing industry. Adsorption research can lead to more efficient and economical technologies for these industries [89,90].

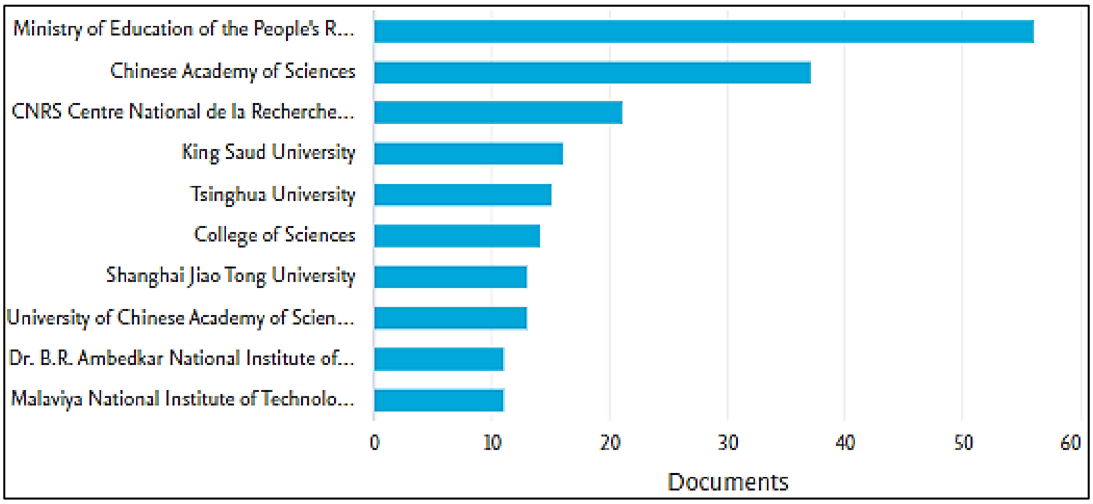

Fig. 9. Leading contribution institution

4.5 Leading Contributing Country

Figure 10 shows the most productive countries in adsorption research from 2019-2024. The countries that are widely recognized for their adsorption research results are countries located in the Asian continent (such as China, India, Saudi Arabia, and South Korea), the American continent (such as United State, Brazil, and Canada), and the European continent (Italy, Germany, and England). China is the country with the most contributions in this study which is then followed by India. In addition, the third most contributing position is the United States. China, India, and the United States are assumed to be productive in producing articles on this topic because the number of articles produced is more than 125. Meanwhile, the remaining seven countries produced fewer than 50 articles. These three countries stand out in adsorption research for the following reasons:

i. China faces significant air and water pollution, driving research into adsorption technologies for pollution mitigation [91].
ii. India faces huge challenges in providing clean water to its large population, making adsorption technologies important for water treatment [3].
iii. The US has a robust research funding system through agencies such as the National Science Foundation (NSF) and the Environmental Protection Agency (EPA).

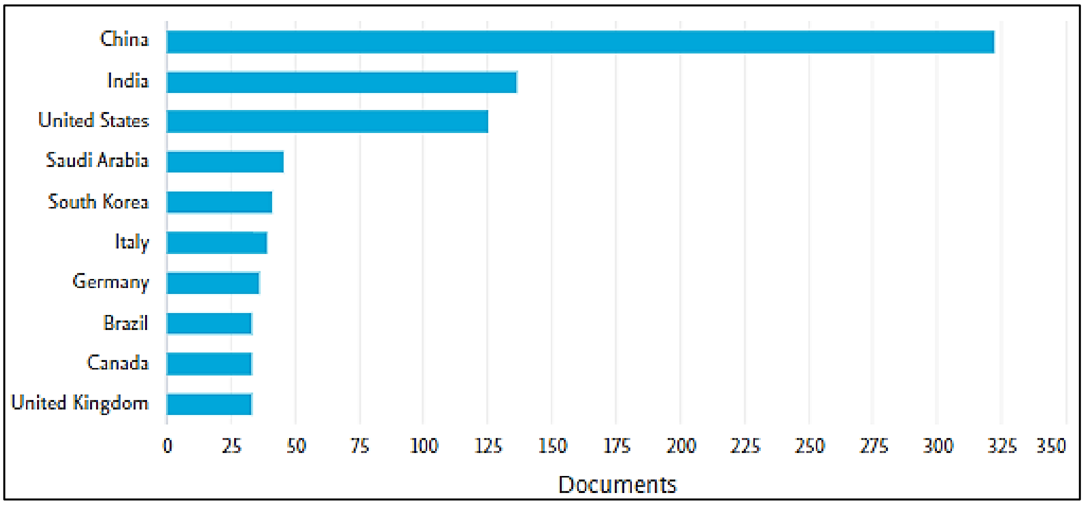

Fig. 10. The most contributing countries

The contributions of different countries in the advancement of adsorption processes involve diverse innovations and research, according to the local and global challenges faced. Here are some of the key contributions highlighted in the literature:

i. Afrika and Asia Tenggara (Malaysia, Indonesia, Thailand): Research in Southeast Asia and Africa focuses on creating locally available resources, such as low-cost, eco-friendly adsorbents made from industrial, agricultural, and household waste [92-94]. Nigeria and Kenya, for instance, have employed biochar made from agricultural waste—such as sawdust, banana peels, and coconut shells—to extract heavy metals from wastewater [95,96]. The potential of chitosan derived from marine trash to absorb colors and organic contaminants has also been highlighted by research conducted in Egypt. Similar developments in the use of local organic waste are observed in Southeast Asia [97,98]. Activated carbon, which effectively removes heavy metals like lead and mercury, is made in Indonesia from sugarcane bagasse and coffee waste [99,100]. Malaysia and Thailand are creating cost-effective and efficient adsorbents from food waste, such as fish waste and durian skin [101,102]. The region's emphasis on sustainability is a reflection of its desire to preserve the environment, lower production costs, and use trash as a resource.

ii. Asia and America: Countries in East Asia and America have utilized advanced technology to develop innovative adsorbent materials. In the development of carbon-based nanotechnology and metal-organic frameworks (MOFs), which are used to adsorb a variety of contaminants, including heavy metals and complex organic molecules, China is at the forefront [103,104]. Utilizing industrial waste to produce high-performance adsorbents has been the subject of research by the Chinese Academy of Sciences and other prestigious universities. Carbon-based adsorbents, like graphene oxide and carbon nanotubes, are the main emphasis in Japan because of their huge surface areas and superior adsorption efficiency for organic molecules that are soluble in water [105,106]. Conversely, South Korea is emphasizing studies on the effectiveness of adsorbent regeneration and recycling of materials such as ionic resins and nano-based polymer membranes [107]. To solve the problems of air and water pollution, research in the US frequently focuses on MOFs and graphene-based materials [108,109]. One significant issue in contemporary water treatment is the removal of pharmaceutical chemicals from wastewater, which has been effectively accomplished by graphene-based adsorbents. Furthermore, US industry-academia cooperation is propelling the creation of long-lasting and reasonably priced adsorbents for widespread use.

iii. Europe: Europe has adopted a multidisciplinary approach to adsorption research, combining materials science, environmental chemistry and engineering technology. For instance, Germany and the Netherlands are creating adsorbents with optimum porosity for certain contaminants using computer-based simulations. Integration with cutting-edge wastewater treatment systems, including the use of membranes based on activated carbon to remove mixed contaminants in industrial wastewater, is another common research topic in these nations [110]. Also, sustainability is the primary focus in the UK, where research is being conducted to create reusable adsorbents for wastewater treatment, such as ionic resins and regenerable silica-based materials [111]. Adsorbents that can function under harsh environmental circumstances, such as water with extremely low or extremely high acidity, are being researched by Nordic nations like Sweden and Norway. Europe is also leading the way in developing new materials such as silica gel, alumina and activated carbon tailored for a wide range of applications, including toxic gas treatment and energy storage [112].

In addition to local demands, global issues including sustainability and air and water pollution are driving adsorption research in several parts of the world. Every region contributes in a different and significant way, from waste management in Africa and Southeast Asia to advances in nanotechnology in East Asia and the Americas and multidisciplinary approaches in Europe. The advancement of adsorption technology is being accelerated by cross-regional partnerships, creating new avenues for more sustainable and efficient solutions.

4.6 Document by Type and Subject Area

Figure 11 shows the characteristics of document types, including 83.8% articles, 10.8% reviews, 2.2% book chapters, 1.7% conference papers, and 0.8% conference reviewers. The rest are other types of publications, and it is normal for there to be a small number of publications, the proportion of which is close to zero, such as notes. Regarding research fields as shown in Figure 12, there are four dominant research fields for this topic, including Chemistry, Environmental Science, Chemical Engineering, and Materials Science where the number of publications in these research fields is more than 14% due to several reasons, including:

i. The field of chemistry involves the interaction between adsorbent and adsorbate molecules, which is a central topic in physical chemistry and surface chemistry.
ii. The field of environmental science involves key technologies for removing contaminants from water and air, which are essential for maintaining a clean and healthy environment.
iii. The field of chemical engineering involves various industrial processes such as gas separation, product purification, and waste treatment, which are the main focus in chemical engineering.
iv. The field of materials involves characterizing the structure and surface properties of adsorbents, which is important for understanding and improving adsorption performance.

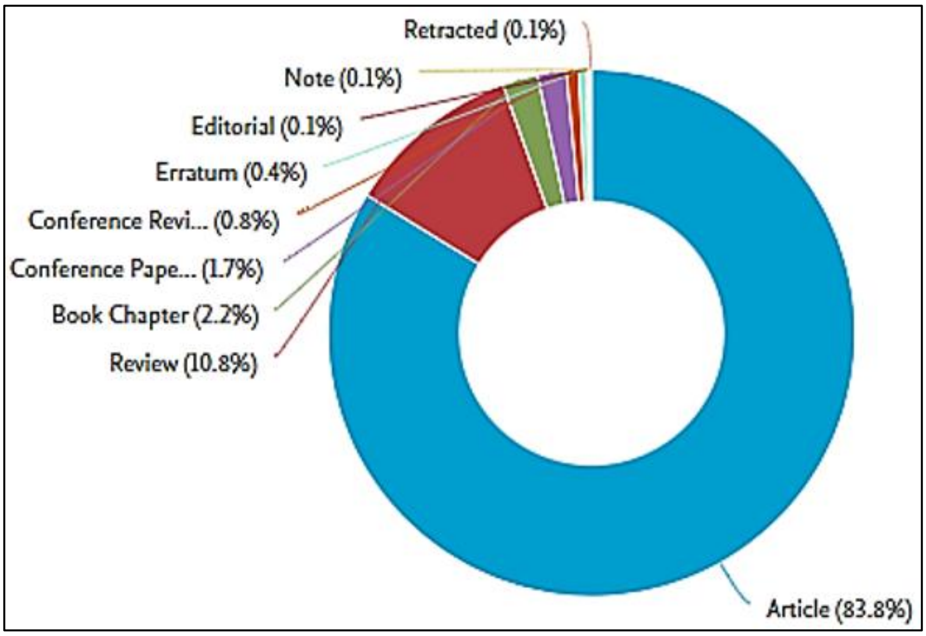

Fig. 11. Publication types in the field of adsorption research

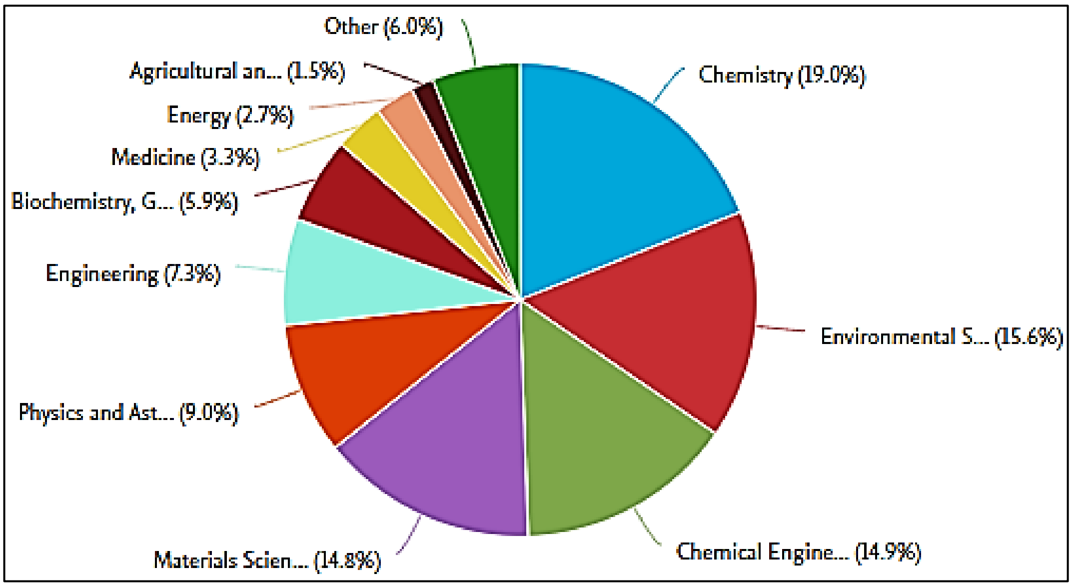

Fig. 12. Distribution of adsorption research documents by subject area

4.7 Network and Overlay Visualization

Figure 13 shows a network visualization that analyzes research fields based on keywords (co-occurrence). The field of terms or terms is extracted based on the title and abstract while the method used to count the dataset is full counting to calculate what is done according to related research. The minimum number of occurrences of a term is 13 documents, resulting in 690 documents that have an occurrence relationship. The terms visualized in this study are marked with colored circles. Different colors indicate different clusters. The size of the circle indicates the frequency of occurrence of the keyword. Larger circles indicate that the keyword is used more often. The distance between the circles is connected by a curved line. The closeness of the distance between the spheres indicates the co-occurrence of the topic. This means that the closer the two or more keywords are, the more often they appear together in an article. The small size of the sphere or the absence of connection between the nodes can suggest that the issue has not been thoroughly investigated or that there is a lack of research emphasis in the field-; thus that research topics with small spheres can be established [113].

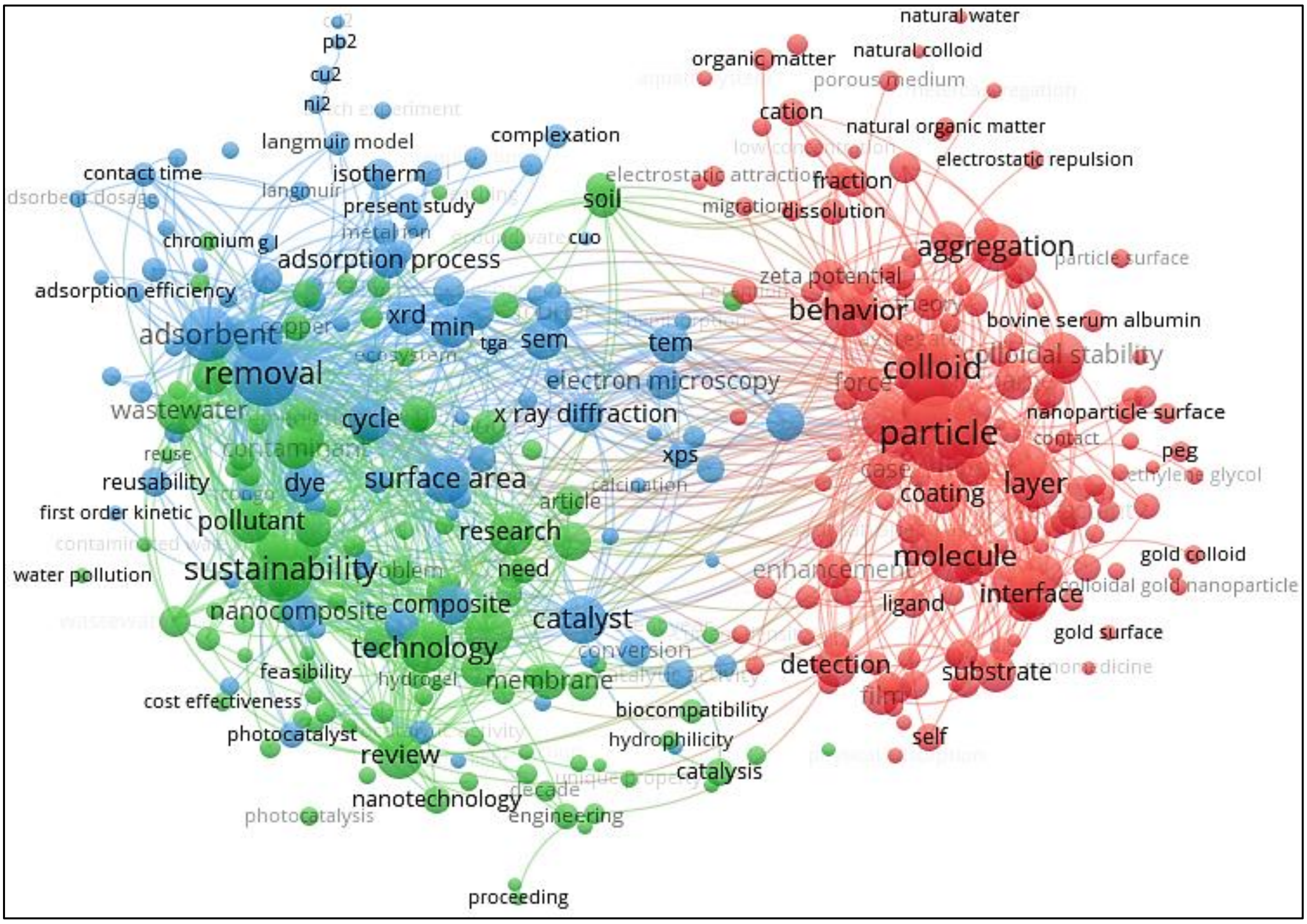

Fig. 13. Network visualization

Based on Figure 13, the network visualization produces 3 clusters, where clusters 1-3 are shown in red, green, blue, yellow, and purple, respectively, with the main clusters being related to particles, sustainability, and removal. Each cluster describes a research area that is interconnected but has a different focus.

i. Cluster 1 (particle and molecule): The main keywords in cluster 1 are particle, colloid, aggregation, behavior, and interface which highlight the importance of understanding the stability, structure, and function of nanoparticles in liquid medium. Stability and aggregation research is an important focus to ensure good dispersion of nanoparticles in solution which plays a role in increasing adsorption efficiency by maximizing particle surface area. Keywords such as interface, molecule, and coating reflect the exploration of the interaction between target molecules (e.g., nickel ions) and nanoparticle surfaces. Surface coatings are used to enhance the selective properties and reactivity of particles towards specific contaminants. Nanoparticles with colloidal properties are used as adsorbents to remove heavy metal ions such as nickel from wastewater. Research in this cluster demonstrates particle engineering-based approaches to improve the efficiency of contaminant removal processes.
ii. Cluster 2 (sustainability and adsorption technology): Cluster 2 connects themes oriented towards green technologies and innovation-based solutions to address water pollution. Keywords such as sustainability, technology, pollutant, removal, and nanotechnology reflect a shift in focus towards sustainable approaches that consider efficiency and environmental impact. The emphasis on adsorption process efficiency and material reusability indicates an effort to reduce waste generated during treatment. This research often focuses on developing materials with the ability to regenerate after use. Research in this cluster includes the exploration of various technologies such as membranes, photocatalysts and nanocomposites. These materials are designed to address contaminants such as heavy metals, including nickel, by integrating sustainability principles. The cluster also covers topics such as cost-effectiveness and feasibility, which are key concerns in large-scale applications. Nanotechnology-based solutions are expected to be implemented economically to meet the global need for clean water treatment.
iii. Cluster 3 (adsorption process and material characteristics): Cluster 3 focuses on the mechanism and characterization of materials involved in the adsorption process. Keywords such as adsorption process, removal efficiency, surface area, x-ray diffraction, and electron microscopy describe the approaches used to understand the performance of adsorbent materials. This research includes adsorption kinetics and thermodynamics studies to evaluate the removal efficiency of nickel ions from waste solutions. Measurements such as maximum adsorption capacity and adsorption velocity are often the main focus. Keywords such as X-ray diffraction (XRD), electron microscopy (TEM, SEM), and surface area demonstrate the importance of characterization techniques to understand the structure and morphology of adsorbent materials. These characterization results are used to optimize material design and performance. This cluster supports innovation in the development of materials with special properties, such as large surface area, high porosity, and high affinity to heavy metal ions.

Figure 14 is a mapping of research topics based on overlay visualization based on historical traces or years of research publication. The overlay visualization analysis was conducted to identify and detect the state of the art of research in nanotechnology conducted in the period 2014-2024. In this visualization, the color of the spheres represents keywords that indicate the year of publication. The purpose of the overlay analysis is to understand changes and trends in research focus over time. This helps in determining how research interests change over time and identifying topics or subjects that get more attention in a given period. The different colors of the overlay visualization results show the research evolution of certain keywords, where lighter colors indicate terms that have not been researched recently [114]. Eight recently researched terms are marked in yellow, most of which are members of cluster 2 (see Figure 14) such as adsorption research on the removal of organic and inorganic pollutants (dyes and heavy metals), sustainability, adsorption cycles, reusability, adsorbent material development, metal organic framework, removal efficiency, and technology.

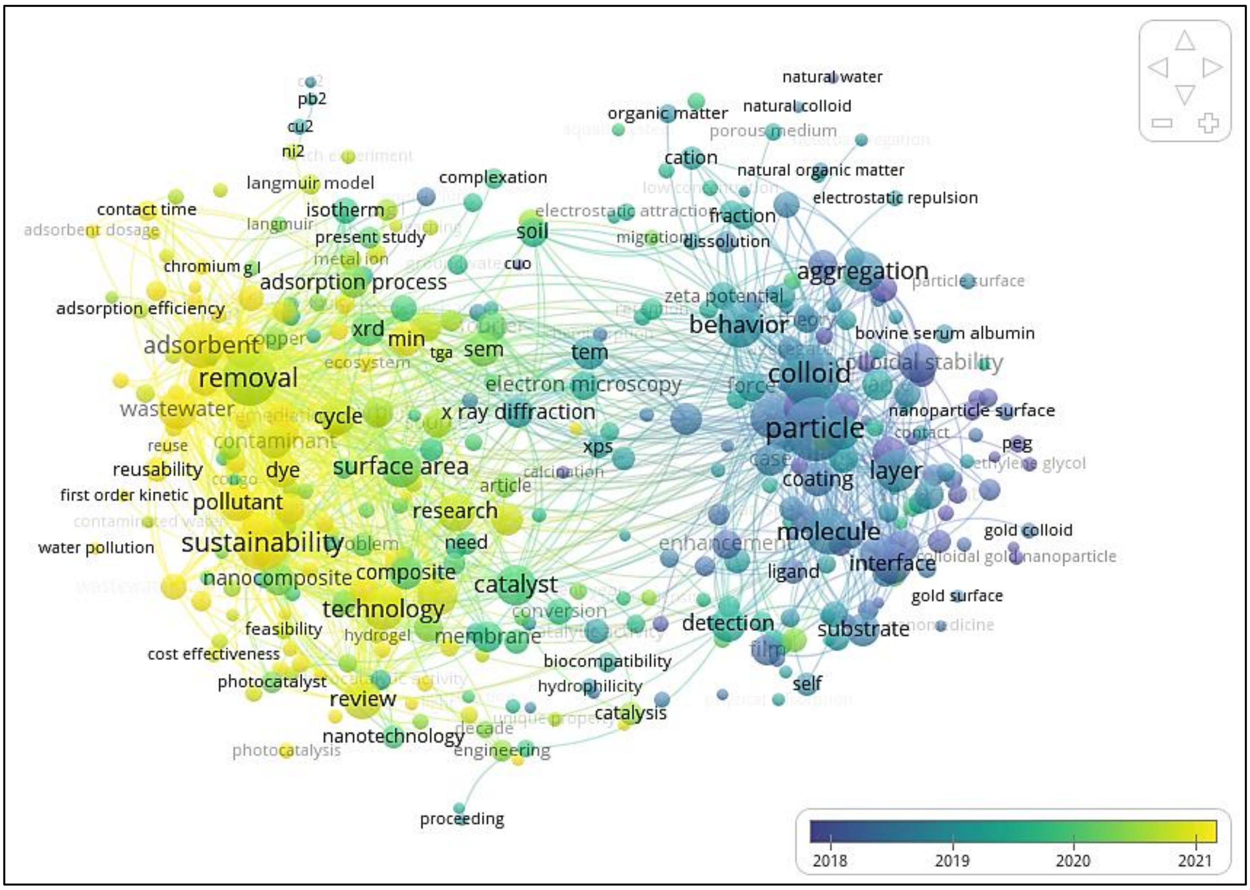

Fig. 14. Overlay visualization

The research trends in this field from 2018 to 2021 are described as follows:

i. Period 2018 (initial research period, blue color): In this period, research focused on the fundamentals of nanomaterials and colloidal properties. Keywords such as particle, colloid, aggregation, stability, and behavior dominated. This reflects the early focus on physicochemical characterization of nanoparticles, including colloidal stability, zeta potential, and molecular interactions. This research aims to understand the fundamental mechanisms of nanoparticles as adsorbent materials.
ii. Period 2019-2020 (application and technology development period, green color): During this period, the research focus began to shift to the application of nanotechnology for effluent treatment. Keywords such as adsorption process, removal, surface area, sustainability, and nanotechnology indicate an increased interest in the removal efficiency of contaminants such as nickel ions using nano-based materials. In addition, keywords such as catalyst, nanocomposite, and technology highlight the development of new materials that have superior properties in capturing contaminants, such as high surface area and chemical stability.
iii. Period 2021 (a period that focuses on sustainability and innovation, yellow color): In recent years, research has focused on aspects of sustainability and process efficiency. Keywords

such as sustainability, reuse, cost-effectiveness, and wastewater have become more prominent. This indicates a shift towards environmentally friendly solutions, where adsorbent materials must not only be efficient but also reusable to reduce waste. In addition, research is also starting to integrate other technologies such as photocatalysis and hydrogels to improve adsorption performance.

5. Conclusions

The main conclusions from the bibliometric analysis include:

i. Over 10 years, from 2014-2024, publications regarding adsorption research predictions have increased significantly from 2021 to 2022 due to increased public interest in environmental awareness due to important world agreements.
ii. The most influential research, when viewed from the number of citations is research that highlights the sustainable characteristics of adsorption by utilizing nano-sized environmentally friendly adsorbent materials.
iii. Journal of Colloid and Interface Science is the most popular journal for research in this study topic, which focuses mainly on colloid and surface interface research.
iv. The most influential institutions in this research are those from China, such as the Ministry of Education of the People's Republic of China and the Chinese Academy of Science because many industries in China require adsorption technology for various purposes, ranging from gas separation in the chemical industry to waste treatment in the manufacturing industry.
v. The most influential countries are China, India, and the United States because they have a myriad of scientific research results related to adsorption.
vi. There are 8 different types of documents on the topic of adsorption research, of which 83.3% of the documents are published in the form of articles, mainly in the research fields of Chemistry, Environmental Science, Chemical Engineering, and Materials Science.
vii. Visualization shows that this research topic consists of 3 clusters with the main clusters being particle-related, sustainability, and removal.
viii. The overlay visualization results show eight terms that have not been recently researched, such as removal studies of organic and inorganic pollutants (dyes and heavy metals), sustainability, adsorption cycle, reusability, adsorbent material development, metal organic framework, removal efficiency, and technology.

There is a lot of promise for future studies on adsorption using sustainable materials as adsorbents to offer green waste management solutions, particularly for garbage that contains heavy metals. This method may effectively create adsorbents while also making use of a lot of waste. To increase the adsorption capacity, biochar must be modified chemically or physically using techniques like metal impregnation and chemical activation. It is also crucial to have a thorough grasp of the adsorption mechanism, including chemical interactions like surface complexation, ion exchange, and reduction. Additionally, a calculated move to combat environmental contamination is the development of large-scale biochar uses for wastewater purification, both residential and commercial. The sustainability and financial viability of biochar will be guaranteed by life cycle analysis and cost assessment. Leading nations in this field of study, like the United States, China, and India, have shown how crucial international cooperation is.

More investigation is required to determine whether biochar is stable enough to be used repeatedly and how to recycle it after usage. Further minimising environmental effects can be achieved through the optimisation of production technologies, such as low-temperature pyrolysis. Through the integration of these diverse elements, adsorption research employing sustainable materials has significant promise as the primary means of efficiently, economically, and ecologically handling heavy metal waste.

References

[1] Gómez-Sanabria, Adriana, Eric Zusman, Lena Höglund-Isaksson, Zbigniew Klimont, So-Young Lee, Kaoru Akahoshi, and Hooman Farzaneh. "Sustainable wastewater management in Indonesia's fish processing industry: Bringing governance into scenario analysis." *Journal of Environmental Management* 275 (2020): 111241. https://doi.org/10.1016/j.jenvman.2020.111241

[2] Jumaidin, Ridhwan, Zulhelmi Asyul Sutan Saidi, Rushdan Ahmad Ilyas, Mohd Nazri Ahmad, Mohammad Khalid Wahid, Mohd Yuhazri Yaakob, Nurul Ain Maidin, Mohd Hidayat Ab Rahman, and Mohd Hairizal Osman. "Characteristics of cogon grass fibre reinforced thermoplastic cassava starch biocomposite: Water absorption and physical properties." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 62, no. 1 (2019): 43-52.

[3] Hussin, Mohamed Saiful Firdaus, Mohd Afdhal Shamsuddin, Ridhwan Jumaidin, Azrul Abidin Zakaria, and Norhisyam Jenal. "Portable grease trap for wastewater management system: A conceptual design approach." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 49, no. 1 (2018): 18-24.

[4] Thanigaivel, S., A. K. Priya, Lalitha Gnanasekaran, Tuan KA Hoang, Saravanan Rajendran, and Matias Soto-Moscoso. "Sustainable applicability and environmental impact of wastewater treatment by emerging nanobiotechnological approach: Future strategy for efficient removal of contaminants and water purification." *Sustainable Energy Technologies and Assessments* 53 (2022): 102484. https://doi.org/10.1016/j.seta.2022.102484

[5] Ghazal, Heba, Elena Koumaki, John Hoslett, Simos Malamis, Evina Katsou, Damia Barcelo, and Hussam Jouhara. "Insights into current physical, chemical and hybrid technologies used for the treatment of wastewater contaminated with pharmaceuticals." *Journal of Cleaner Production* 361 (2022): 132079. https://doi.org/10.1016/j.jclepro.2022.132079

[6] Vardhan, Kilaru Harsha, Ponnusamy Senthil Kumar, and Rames C. Panda. "A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives." *Journal of Molecular Liquids* 290 (2019): 111197. https://doi.org/10.1016/j.molliq.2019.111197

[7] Rathi, B. Senthil, P. Senthil Kumar, and Dai-Viet N. Vo. "Critical review on hazardous pollutants in water environment: Occurrence, monitoring, fate, removal technologies and risk assessment." *Science of the Total Environment* 797 (2021): 149134. https://doi.org/10.1016/j.scitotenv.2021.149134

[8] Peng, Hao, and Jing Guo. "Removal of chromium from wastewater by membrane filtration, chemical precipitation, ion exchange, adsorption electrocoagulation, electrochemical reduction, electrodialysis, electrodeionization, photocatalysis and nanotechnology: a review." *Environmental Chemistry Letters* 18, no. 6 (2020): 2055-2068. https://doi.org/10.1007/s10311-020-01058-x

[9] Donkadokula, Naresh Yadav, Anand Kishore Kola, Iffat Naz, and Devendra Saroj. "A review on advanced physico-chemical and biological textile dye wastewater treatment techniques." *Reviews in Environmental Science and Bio/Technology* 19 (2020): 543-560. https://doi.org/10.1007/s11157-020-09543-z

[10] Ragadhita, Risti, and Asep Bayu Dani Nandiyanto. "How to calculate adsorption isotherms of particles using two-parameter monolayer adsorption models and equations." *Indonesian Journal of Science and Technology* 6, no. 1 (2021): 205-234. https://doi.org/10.17509/ijost.v6i1.32354

[11] Sayuti, Rabiatul'Adawiyah. "Effect of particle size on physical properties of rambutan seed powder." *Journal of Research in Nanoscience and Nanotechnology* 7, no. 2 (2023): 1-8. https://doi.org/10.37934/jrnn.7.2.18

[12] Nandiyanto, Asep Bayu Dani, Meli Fiandini, Denaya Ayu Fadiah, Pitri Aprilia Muktakin, Risti Ragadhita, Willy Cahya Nugraha, Teguh Kurniawan, Muhammad Roil Bilad, Jumril Yunas, and Abdulkareem Sh Mahdi Al Obaidi. "Sustainable biochar carbon microparticles based on mangosteen peel as biosorbent for dye removal: Theoretical review, modelling, and adsorption isotherm characteristics." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 105, no. 1 (2023): 41-58. https://doi.org/10.37934/arfmts.105.1.4158

[13] Nandiyanto, Asep Bayu Dani, Zulfa Fathi Arinalhaq, Salma Rahmadianti, Mauseni Wantika Dewi, Yulian Putri Chandra Rizky, Aulia Maulidina, Sri Anggraeni, Muhammad Roil Bilad, and Jumril Yunas. "Curcumin adsorption on carbon microparticles: Synthesis from soursop (Annona muricata L.) peel waste, adsorption isotherms and thermodynamic and adsorption mechanism." *International Journal of Nanoelectronics & Materials* 13 (2020).

[14] Nandiyanto, Asep Bayu Dani, Risti Ragadhita, M. Fiandini, and R. Maryanti. "Curcumin dye adsorption in aqueous solution by carbon-based date palm seed: Preparation, characterization, and isotherm adsorption." *Journal of*

Applied Research and Technology 21, no. 5 (2023): 808-824. https://doi.org/10.22201/icat.24486736e.2023.21.5.1972
[15] Nandiyanto, Asep Bayu Dani, Meli Fiandini, Risti Ragadhita, Hanifa Maulani, Muthia Nurbaiti, Abdulkareem Sh Mahdi Al-Obaidi, Jumril Yunas, and Muhammad Roil Bilad. "Sustainable biochar carbon biosorbent based on tamarind (Tamarindus indica L) seed: Literature review, preparation, and adsorption isotherm." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 32, no. 1 (2023): 210-226. https://doi.org/10.37934/araset.32.1.210226
[16] Nandiyanto, Asep Bayu Dani, Risti Ragadhita, and Jumril Yunas. "Adsorption isotherm of densed monoclinic tungsten trioxide nanoparticles." *Sains Malaysiana* 49, no. 12 (2020): 2881-2890. https://doi.org/10.17576/jsm-2020-4912-01
[17] Nandiyanto, Asep Bayu Dani, Siti Nur Hofifah, Hilma Tahsilul Inayah, Silmi Ridwan Putri, Siti Saffanah Apriliani, Sri Anggraeni, Dian Usdiyana, and Ali Rahmat. "Adsorption isotherm of carbon microparticles prepared from pumpkin (Cucurbita maxima) seeds for dye removal." *Iraqi Journal of Science* (2021): 1404-1414. https://doi.org/10.24996/ijs.2021.62.5.2
[18] N'diaye, Abdoulaye Demba, Mohamed Sid'Ahmed Kankou, Belkheir Hammouti, Asep Bayu Dani Nandiyanto, and Dwi Fitria Al Husaeni. "A review of biomaterial as an adsorbent: From the bibliometric literature review, the definition of dyes and adsorbent, the adsorption phenomena and isotherm models, factors affecting the adsorption process, to the use of typha species waste as adsorbent." *Communications in Science and Technology* 7, no. 2 (2022): 140-153. https://doi.org/10.21924/cst.7.2.2022.977
[19] Ragadhita, R., A. Amalliya, S. Nuryani, M. Fiandini, A. B. D. Nandiyanto, A. Hufad, A. Mudzakir, W. C. Nugraha, O. Farobie, I. Istadi, A.S.M. Al-Obaidi. "Sustainable carbon-based biosorbent particles from papaya seed waste: preparation and adsorption isotherm." *Moroccan Journal of Chemistry* 11, no. 2 (2023): 395-410. https://doi.org/10.48317/IMIST.PRSM/morjchem-v11i2.38263
[20] Nandiyanto, Asep Bayu Dani, Rina Maryanti, Meli Fiandini, Risti Ragadhita, Dian Usdiyana, Sri Anggraeni, Wafa Raihana Arwa, and Abdulkareem Sh Mahdi Al-Obaidi. "Synthesis of carbon microparticles from red dragon fruit (Hylocereus undatus) peel waste and their adsorption isotherm characteristics." *Molekul* 15, no. 3 (2020): 199-209. https://doi.org/10.20884/1.jm.2020.15.3.657
[21] Shameli, Kamyar, Zahra Izadiyan, Pooneh Kia, Hemra Hamrayev, Hossein Jahangirian, Aras Kartouzian, Emad Abbas Jaffar Al-Mulla, and Hassan Moeini. "Exploring the potential of gold nanoparticles in nanomedicine: A comprehensive analysis of benefits and limitations." *Journal of Research in Nanoscience and Nanotechnology* 11, no. 1 (2024): 1-15. https://doi.org/10.37934/jrnn.11.1.115
[22] Rai, Prabhat Kumar, Vanish Kumar, SangSoo Lee, Nadeem Raza, Ki-Hyun Kim, Yong Sik Ok, and Daniel CW Tsang. "Nanoparticle-plant interaction: Implications in energy, environment, and agriculture." *Environment International* 119 (2018): 1-19. https://doi.org/10.1016/j.envint.2018.06.012
[23] Guimarães, Milena Lima, Fernando Antônio Gomes da Silva, Mateus Matiuzzi da Costa, and Helinando Pequeno de Oliveira. "Green synthesis of silver nanoparticles using Ziziphus joazeiro leaf extract for production of antibacterial agents." *Applied Nanoscience* 10 (2020): 1073-1081. https://doi.org/10.1007/s13204-019-01181-4
[24] Rai, Prabhat Kumar, Ki-Hyun Kim, Sang Soo Lee, and Jin-Hong Lee. "Molecular mechanisms in phytoremediation of environmental contaminants and prospects of engineered transgenic plants/microbes." *Science of the Total Environment* 705 (2020): 135858. https://doi.org/10.1016/j.scitotenv.2019.135858
[25] Rai, Prabhat Kumar, and J. S. Singh. "Invasive alien plant species: Their impact on environment, ecosystem services and human health." *Ecological indicators* 111 (2020): 106020. https://doi.org/10.1016/j.ecolind.2019.106020
[26] Heidarinejad, Zoha, Mohammad Hadi Dehghani, Mohsen Heidari, Gholamali Javedan, Imran Ali, and Mika Sillanpää. "Methods for preparation and activation of activated carbon: a review." *Environmental Chemistry Letters* 18 (2020): 393-415. https://doi.org/10.1007/s10311-019-00955-0
[27] Zhou, Yong, Lei Zhang, and Zhengjun Cheng. "Removal of organic pollutants from aqueous solution using agricultural wastes: a review." *Journal of Molecular Liquids* 212 (2015): 739-762. https://doi.org/10.1016/j.molliq.2015.10.023
[28] Ghazali, Mohd Fairusham, Muhammad Ilham Maulana, Nor Azwadi Che Sidik, Gholamhassan Najafi, Muhammad Ikram Mohd Rashid, Mohd Faizal Jamlos, Mohammadreza Hasandust Rostami, and Ahmad Najafpour. "Experimental analysis and CFD Simulation of photovoltaic/thermal system with nanofluids for sustainable energy solution." *Journal of Advanced Research in Numerical Heat Transfer* 24, no. 1 (2024): 1-13. https://doi.org/10.37934/arnht.24.1.113
[29] Kyzas, George Z., and Margaritis Kostoglou. "Green adsorbents for wastewaters: a critical review." Materials 7, no. 1 (2014): 333-364. https://doi.org/10.3390/ma7010333
[30] Omo-Okoro, Patricia N., Adegbenro P. Daso, and Jonathan O. Okonkwo. "A review of the application of agricultural wastes as precursor materials for the adsorption of per-and polyfluoroalkyl substances: A focus on current

approaches and methodologies." *Environmental Technology & Innovation* 9 (2018): 100-114. https://doi.org/10.1016/j.eti.2017.11.005

[31] Dai, Yingjie, Qiya Sun, Wensi Wang, Lu Lu, Mei Liu, Jingjing Li, Shengshu Yang, Yue Sun, Kexin Zhang, Jiayi Xu, Wenlei Zheng, Zhaoyue Hu, Yahan Yang, Yuewen Gao, Yanjun Chen, Xu Zhang, Feng Gao, and Ying Zhang. "Utilizations of agricultural waste as adsorbent for the removal of contaminants: A review." *Chemosphere* 211 (2018): 235-253. https://doi.org/10.1016/j.chemosphere.2018.06.179

[32] Jothirani, R., P. Senthil Kumar, A. Saravanan, Abishek S. Narayan, and Abhishek Dutta. "Ultrasonic modified corn pith for the sequestration of dye from aqueous solution." *Journal of Industrial and Engineering Chemistry* 39 (2016): 162-175. https://doi.org/10.1016/j.jiec.2016.05.024

[33] Yaashikaa, P. R., P. Senthil Kumar, Sunita J. Varjani, and A. Saravanan. "Advances in production and application of biochar from lignocellulosic feedstocks for remediation of environmental pollutants." *Bioresource Technology* 292 (2019): 122030. https://doi.org/10.1016/j.biortech.2019.122030

[34] Kaveeshwar, Aditya Rajeev, Ponnusamy Senthil Kumar, Emmanuel D. Revellame, Daniel D. Gang, Mark E. Zappi, and Ramalingam Subramaniam. "Adsorption properties and mechanism of barium (II) and strontium (II) removal from fracking wastewater using pecan shell based activated carbon." *Journal of Cleaner Production* 193 (2018): 1-13. https://doi.org/10.1016/j.jclepro.2018.05.041

[35] Temdrara, L., A. Addoun, and A. Khelifi. "Development of olivestones-activated carbons by physical, chemical and physicochemical methods for phenol removal: a comparative study." *Desalination and Water Treatment* 53, no. 2 (2015): 452-461. https://doi.org/10.1080/19443994.2013.838523

[36] Mo, Jiahao, Qi Yang, Na Zhang, Wenxiang Zhang, Yi Zheng, and Zhien Zhang. "A review on agro-industrial waste (AIW) derived adsorbents for water and wastewater treatment." *Journal of Environmental Management* 227 (2018): 395-405. https://doi.org/10.1016/j.jenvman.2018.08.069

[37] Kushwaha, S., G. Sreelatha, and P. Padmaja. "Evaluation of acid-treated palm shell powder for its effectiveness in the adsorption of organophosphorus pesticides: isotherm, kinetics, and thermodynamics." *Journal of Chemical & Engineering Data* 56, no. 5 (2011): 2407-2415. https://doi.org/10.1021/je1013334

[38] Deokar, Sunil K., Sachin A. Mandavgane, and Bhaskar D. Kulkarni. "Agro-industrial waste: a low-cost adsorbent for effective removal of 4-chloro-2-methylphenoxyacetic acid herbicide in batch and packed bed modes." *Environmental Science and Pollution Research* 23 (2016): 16164-16175. https://doi.org/10.1007/s11356-016-6769-z

[39] Gu, Shiqing, Xiaonan Kang, Lan Wang, Eric Lichtfouse, and Chuanyi Wang. "Clay mineral adsorbents for heavy metal removal from wastewater: a review." *Environmental Chemistry Letters* 17 (2019): 629-654. https://doi.org/10.1007/s10311-018-0813-9

[40] Ponnuchamy, Muthamilselvi, Ashish Kapoor, Ponnusamy Senthil Kumar, Dai-Viet N. Vo, Akash Balakrishnan, Meenu Mariam Jacob, and Prabhakar Sivaraman. "Sustainable adsorbents for the removal of pesticides from water: a review." *Environmental Chemistry Letters* 19 (2021): 2425-2463. https://doi.org/10.1007/s10311-021-01183-1

[41] Shabeer, TP Ahammed, Ajoy Saha, V. T. Gajbhiye, Suman Gupta, K. M. Manjaiah, and Eldho Varghese. "Simultaneous removal of multiple pesticides from water: effect of organically modified clays as coagulant aid and adsorbent in coagulation–flocculation process." *Environmental Technology* 35, no. 20 (2014): 2619-2627. https://doi.org/10.1080/09593330.2014.914573

[42] Shahbazi, Afsaneh, Rafael Gonzalez-Olmos, Frank-Dieter Kopinke, Pezhman Zarabadi-Poor, and Anett Georgi. "Natural and synthetic zeolites in adsorption/oxidation processes to remove surfactant molecules from water." *Separation and Purification Technology* 127 (2014): 1-9. https://doi.org/10.1016/j.seppur.2014.02.021

[43] Yuna, Zhao. "Review of the natural, modified, and synthetic zeolites for heavy metals removal from wastewater." *Environmental Engineering Science* 33, no. 7 (2016): 443-454. https://doi.org/10.1089/ees.2015.0166

[44] Hendriks, F. C., D. Valencia, P. C. A. Bruijnincx, and B. M. Weckhuysen. "Zeolite molecular accessibility and host–guest interactions studied by adsorption of organic probes of tunable size." *Physical Chemistry Chemical Physics* 19, no. 3 (2017): 1857-1867. https://doi.org/10.1039/C6CP07572J

[45] Yonli, Arsène H., Isabelle Batonneau-Gener, and Jean Koulidiati. "Adsorptive removal of α-endosulfan from water by hydrophobic zeolites. An isothermal study." *Journal of Hazardous Materials* 203 (2012): 357-362. https://doi.org/10.1016/j.jhazmat.2011.12.042

[46] Joshiba, G. Janet, P. Senthil Kumar, M. Govarthanan, P. Tsopbou Ngueagni, and A. F. C. C. Abilarasu. "Investigation of magnetic silica nanocomposite immobilized Pseudomonas fluorescens as a biosorbent for the effective sequestration of Rhodamine B from aqueous systems." *Environmental Pollution* 269 (2021): 116173. https://doi.org/10.1016/j.envpol.2020.116173

[47] Aksu, Zümriye. "Application of biosorption for the removal of organic pollutants: a review." *Process Biochemistry* 40, no. 3-4 (2005): 997-1026. https://doi.org/10.1016/j.procbio.2004.04.008

[48] Abdel–Aty, Azza M., Tarek A. Gad-Allah, Mohamed EM Ali, and Hany H. Abdel-Ghafar. "Parametric, equilibrium, and kinetic studies on biosorption of diuron by Anabaena sphaerica and Scenedesmus obliquus." *Environmental Progress & Sustainable Energy* 34, no. 2 (2015): 504-511. https://doi.org/10.1002/ep.12027

[49] Mohammad, Somaia G., Sahar M. Ahmed, and Abdel Fattah M. Badawi. "A comparative adsorption study with different agricultural waste adsorbents for removal of oxamyl pesticide." *Desalination and Water Treatment* 55, no. 8 (2015): 2109-2120. https://doi.org/10.1080/19443994.2014.930797

[50] Ignatowicz, K. "A mass transfer model for the adsorption of pesticide on coconut shell-based activated carbon." *International Journal of Heat and Mass Transfer* 54, no. 23-24 (2011): 4931-4938.

[51] Foo, Keng Yuen, and Bassim H. Hameed. "Insights into the modeling of adsorption isotherm systems." Chemical engineering journal 156, no. 1 (2010): 2-10. https://doi.org/10.1016/j.ijheatmasstransfer.2011.07.005

[52] Chaparadza, Allen, and Jeanne M. Hossenlopp. "Adsorption kinetics, isotherms and thermodynamics of atrazine removal using a banana peel based sorbent." *Water Science and Technology* 65, no. 5 (2012): 940-947. https://doi.org/10.2166/wst.2012.935

[53] Njoku, V. O., Md Azharul Islam, M. Asif, and B. H. Hameed. "Adsorption of 2, 4-dichlorophenoxyacetic acid by mesoporous activated carbon prepared from H3PO4-activated langsat empty fruit bunch." *Journal of Environmental Management* 154 (2015): 138-144. https://doi.org/10.1016/j.jenvman.2015.02.002

[54] Zhou, Xiaohui, Jianjun Zhou, Yaochi Liu, Yang He, Jialin Ren, and Jing Guo. "Adsorption of endocrine disrupting ethylparaben from aqueous solution by chemically activated biochar developed from oil palm fibre." *Separation Science and Technology* 54, no. 5 (2019): 683-695. https://doi.org/10.1080/01496395.2018.1520723

[55] Memon, G. Zuhra, M. I. Bhanger, Mubeena Akhtar, Farah N. Talpur, and Jamil R. Memon. "Adsorption of methyl parathion pesticide from water using watermelon peels as a low cost adsorbent." *Chemical Engineering Journal* 138, no. 1-3 (2008): 616-621. https://doi.org/10.1016/j.cej.2007.09.027

[56] Ghiaci, M., M. Arshadi, M. E. Sedaghat, R. J. Kalbasi, and A. Gil. "Adsorption of organic pollutants from aqueous solutions on cereal ashes." *Journal of Chemical & Engineering Data* 53, no. 11 (2008): 2707-2709. https://doi.org/10.1021/je800532p

[57] Salman, Jasim M., V. O. Njoku, and Bassim H. Hameed. "Adsorption of pesticides from aqueous solution onto banana stalk activated carbon." *Chemical Engineering Journal* 174, no. 1 (2011): 41-48. https://doi.org/10.1016/j.cej.2011.08.026

[58] Memon, G. Zuhra, M. Moghal, Jamil R. Memon, Nusrat N. Memon, and M. Bhanger. "Adsorption of selected pesticides from aqueous solutions using cost effective walnut shells." *Adsorption* 4, no. 10 (2014): 43-56. https://doi.org/10.9790/3021-041014356

[59] Azarkan, Said, Aránzazu Peña, Khalid Draoui, and C. Ignacio Sainz-Diaz. "Adsorption of two fungicides on natural clays of Morocco." *Applied Clay Science* 123 (2016): 37-46. https://doi.org/10.1016/j.clay.2015.12.036

[60] Trivedi, Nikhilesh S., Sachin A. Mandavgane, and Bhaskar D. Kulkarni. "Mustard plant ash: a source of micronutrient and an adsorbent for removal of 2, 4-dichlorophenoxyacetic acid." *Environmental Science and Pollution Research* 23 (2016): 20087-20099. https://doi.org/10.1007/s11356-016-6202-7

[61] Okumuş, Veysi, K. Serdar Çelik, Sadin Özdemir, Abdurrahman Dündar, and Ersin Kılınç. "Biosorption of chlorophenoxy acid herbicides from aqueous solution by using low-cost agricultural wastes." *Desalination and Water Treatment* 56, no. 7 (2015): 1898-1907. https://doi.org/10.1080/19443994.2014.961562

[62] Mandal, Abhishek, Neera Singh, and T. J. Purakayastha. "Characterization of pesticide sorption behaviour of slow pyrolysis biochars as low cost adsorbent for atrazine and imidacloprid removal." *Science of the Total Environment* 577 (2017): 376-385. https://doi.org/10.1016/j.scitotenv.2016.10.204

[63] Rojas, Raquel, Eva Vanderlinden, José Morillo, José Usero, and Hicham El Bakouri. "Characterization of sorption processes for the development of low-cost pesticide decontamination techniques." *Science of the Total Environment* 488 (2014): 124-135. https://doi.org/10.1016/j.scitotenv.2014.04.079

[64] Cobas, M., J. Meijide, M. A. Sanromán, and M. Pazos. "Chestnut shells to mitigate pesticide contamination." *Journal of the Taiwan Institute of Chemical Engineers* 61 (2016): 166-173. https://doi.org/10.1016/j.jtice.2015.11.026

[65] El Bakouri, Hicham, José Morillo, José Usero, and Abdelhamid Ouassini. "Potential use of organic waste substances as an ecological technique to reduce pesticide ground water contamination." *Journal of Hydrology* 353, no. 3-4 (2008): 335-342. https://doi.org/10.1016/j.jhydrol.2008.02.019

[66] Jumaidin, Ridhwan, Zulhelmi Asyul Sutan Saidi, Rushdan Ahmad Ilyas, Mohd Nazri Ahmad, Mohammad Khalid Wahid, Mohd Yuhazri Yaakob, Nurul Ain Maidin, Mohd Hidayat Ab Rahman, and Mohd Hairizal Osman. "Characteristics of cogon grass fibre reinforced thermoplastic cassava starch biocomposite: Water absorption and physical properties." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 62, no. 1 (2019): 43-52.

[67] Saleman, Abdul Rafeq, Mohamad Shukri Zakaria, Ridhwan Jumaidin, and Mohd Nazmin Maslan. "Ultra-thin liquid film with shear and the influences on thermal energy transfer at solid–liquid interfaces of simple liquid methane in

contact with (110) surface structure of face-centred cubic lattice (FCC)." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 87, no. 3 (2021): 21-30. https://doi.org/10.37934/arfmts.87.3.2130

[68] Gupta, V. K., O. Moradi, I. Tyagi, S. Agarwal, H. Sadegh, R. Shahryari-Ghoshekandi, A. S. H. Makhlouf, M. Goodarzi, and A. Garshasbi. "Study on the removal of heavy metal ions from industry waste by carbon nanotubes: effect of the surface modification: a review." *Critical Reviews in Environmental Science and Technology* 46, no. 2 (2016): 93-118. https://doi.org/10.1080/10643389.2015.1061874

[69] Dehghani, Mohammad Hadi, Shabnam Ahmadi, Soumya Ghosh, Amina Othmani, Christian Osagie, Maryam Meskini, Samar Sami Alkafaas, Alhadji Malloum, Waheed Ahmad Khanday, Ajala Oluwaseun Jacob, Ömür Gökkuş, Andrew Oroke, Obialor Martins Chineme, Rama Rao Karri, Eder C. Lima. "Recent advances on sustainable adsorbents for the remediation of noxious pollutants from water and wastewater: A critical review." *Arabian Journal of Chemistry* 16, no. 12 (2023): 105303. https://doi.org/10.1016/j.arabjc.2023.105303

[70] Tran, Hai Nguyen, Sheng-Jie You, Ahmad Hosseini-Bandegharaei, and Huan-Ping Chao. "Mistakes and inconsistencies regarding adsorption of contaminants from aqueous solutions: a critical review." *Water Research* 120 (2017): 88-116. https://doi.org/10.1016/j.watres.2017.04.014

[71] Trivedi, Nikhilesh S., and Sachin A. Mandavgane. "Fundamentals of 2, 4 dichlorophenoxyacetic acid removal from aqueous solutions." *Separation & Purification Reviews* 47, no. 4 (2018): 337-354. https://doi.org/10.1080/15422119.2018.1450765

[72] Saxena, Reena, Megha Saxena, and Amit Lochab. "Recent progress in nanomaterials for adsorptive removal of organic contaminants from wastewater." *ChemistrySelect* 5, no. 1 (2020): 335-353. https://doi.org/10.1002/slct.201903542

[73] Bhadra, Biswa Nath, Ji Yoon Song, Su-Kyung Lee, Young Kyu Hwang, and Sung Hwa Jhung. "Adsorptive removal of aromatic hydrocarbons from water over metal azolate framework-6-derived carbons." *Journal of Hazardous Materials* 344 (2018): 1069-1077. https://doi.org/10.1016/j.jhazmat.2017.11.057

[74] Wang, Wei, Ayiguli Maimaiti, Huilan Shi, Rongrong Wu, Run Wang, Zelun Li, Delin Qi, Gang Yu, and Shubo Deng. "Adsorption behavior and mechanism of emerging perfluoro-2-propoxypropanoic acid (GenX) on activated carbons and resins." *Chemical Engineering Journal* 364 (2019): 132-138. https://doi.org/10.1016/j.cej.2019.01.153

[75] Alsawy, Tariq, Emanne Rashad, Mohamed El-Qelish, and Ramy H. Mohammed. "A comprehensive review on the chemical regeneration of biochar adsorbent for sustainable wastewater treatment." *NPJ Clean Water* 5, no. 1 (2022): 29. https://doi.org/10.1038/s41545-022-00172-3

[76] Nguyen, Luan Minh, Ngoan Thi Thao Nguyen, Thuy Thi Thanh Nguyen, Thuong Thi Nguyen, Duyen Thi Cam Nguyen, and Thuan Van Tran. "Occurrence, toxicity and adsorptive removal of the chloramphenicol antibiotic in water: a review." *Environmental Chemistry Letters* 20, no. 3 (2022): 1929-1963. https://doi.org/10.1007/s10311-022-01416-x

[77] Al Husaeni, Dwi Fitria, and Asep Bayu Dani Nandiyanto. "Bibliometric using Vosviewer with Publish or Perish (using Google Scholar data): From step-by-step processing for users to the practical examples in the analysis of digital learning articles in pre and post Covid-19 pandemic." *ASEAN Journal of Science and Engineering* 2, no. 1 (2022): 19-46. https://doi.org/10.17509/ajse.v2i1.37368

[78] Sidik, Nor Azwadi Che, Asep Bayu Dani Nandiyanto, and Dwi Novia Al Husaeni. "Introducing semarak ilmu publishing in publishing science and engineering: Bibliometric analysis." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 49, no. 1 (2025): 26-53. https://doi.org/10.37934/araset.49.1.2653

[79] Liu, Xiaomeng, Hongyan Gao, Joy E. Ward, Xiaorong Liu, Bing Yin, Tianda Fu, Jianhan Chen, Derek R. Lovley, and Jun Yao. "Power generation from ambient humidity using protein nanowires." *Nature* 578, no. 7796 (2020): 550-554. https://doi.org/10.1038/s41586-020-2010-9

[80] Dai, Dihua, Zheng Li, Jie Yang, Chunyu Wang, Jia-Rui Wu, Yan Wang, Dongmei Zhang, and Ying-Wei Yang. "Supramolecular assembly-induced emission enhancement for efficient mercury (II) detection and removal." *Journal of the American Chemical Society* 141, no. 11 (2019): 4756-4763. https://doi.org/10.1021/jacs.9b01546

[81] Li, Zhe, Yuqing Sun, Yang Yang, Yitong Han, Tongshuai Wang, Jiawei Chen, and Daniel CW Tsang. "Biochar-supported nanoscale zero-valent iron as an efficient catalyst for organic degradation in groundwater." *Journal of Hazardous Materials* 383 (2020): 121240. https://doi.org/10.1016/j.jhazmat.2019.121240

[82] Choudhary, Manisha, Rahul Kumar, and Sudarsan Neogi. "Activated biochar derived from Opuntia ficus-indica for the efficient adsorption of malachite green dye, Cu+ 2 and Ni+ 2 from water." *Journal of Hazardous Materials* 392 (2020): 122441. https://doi.org/10.1016/j.jhazmat.2020.122441

[83] Jiang, Wenfeng, Zhi-bei Qu, Prashant Kumar, Drew Vecchio, Yuefei Wang, Yu Ma, Joong Hwan Bahng, Kalil Bernardino, Weverson R. Gomes, Felippe M. Colombari, Asdrubal Lozada-Blanco, Michael Veksler, Emanuele Marino, Alex Simon, Christopher Murray, Sérgio Ricardo Muniz, André F. de Moura, and Nicholas A. Kotov. "Emergence of complexity in hierarchically organized chiral particles." *Science* 368, no. 6491 (2020): 642-648. https://doi.org/10.1126/science.aaz7949

[84] Rahmani-Sani, Abolfazl, Pardeep Singh, Pankaj Raizada, Eder Claudio Lima, Ioannis Anastopoulos, Dimitrios A. Giannakoudakis, Selvaraju Sivamani, Tetiana A. Dontsova, and Ahmad Hosseini-Bandegharaei. "Use of chicken feather and eggshell to synthesize a novel magnetized activated carbon for sorption of heavy metal ions." *Bioresource Technology* 297 (2020): 122452. https://doi.org/10.1016/j.biortech.2019.122452

[85] Abdollahi, Nasrin, Sayed Ali Akbar Razavi, Ali Morsali, and Mao-Lin Hu. "High capacity Hg (II) and Pb (II) removal using MOF-based nanocomposite: Cooperative effects of pore functionalization and surface-charge modulation." *Journal of Hazardous Materials* 387 (2020): 121667. https://doi.org/10.1016/j.jhazmat.2019.121667

[86] Davranche, Mélanie, Cloé Veclin, Anne-Catherine Pierson-Wickmann, Hind El Hadri, Bruno Grassl, Laura Rowenczyk, Aline Dia, Alexandra Ter Halle, Florent Blancho, Stephanie Reynaud, and Julien Gigault."Are nanoplastics able to bind significant amount of metals? The lead example." Environmental pollution 249 (2019): 940-948. https://doi.org/10.1016/j.envpol.2019.03.087

[87] Hu, Dalin, Ran Jiang, Nan Wang, Hongping Xu, Yang-Guang Wang, and Xiao-kun Ouyang. "Adsorption of diclofenac sodium on bilayer amino-functionalized cellulose nanocrystals/chitosan composite." *Journal of Hazardous Materials* 369 (2019): 483-493. https://doi.org/10.1016/j.jhazmat.2019.02.057

[88] Zhang, Wanyu, Hai Xu, Fei Xie, Xiaohua Ma, Bo Niu, Mingqi Chen, Hongyu Zhang, Yayun Zhang, and Donghui Long. "General synthesis of ultrafine metal oxide/reduced graphene oxide nanocomposites for ultrahigh-flux nanofiltration membrane." *Nature Communications* 13, no. 1 (2022): 471. https://doi.org/10.1038/s41467-022-28180-4

[89] Shi, Jingxin, Wenping Huang, Hongjun Han, and Chunyan Xu. "Pollution control of wastewater from the coal chemical industry in China: Environmental management policy and technical standards." *Renewable and Sustainable Energy Reviews* 143 (2021): 110883. https://doi.org/10.1016/j.rser.2021.110883

[90] Hussin, Farihahusnah, and Mohamed Kheireddine Aroua. "Recent trends in the development of adsorption technologies for carbon dioxide capture: A brief literature and patent reviews (2014–2018)." *Journal of Cleaner Production* 253 (2020): 119707. https://doi.org/10.1016/j.jclepro.2019.119707

[91] Ding, Yin, Jun Zhao, Jia-Wei Liu, Jizhi Zhou, Liang Cheng, Jia Zhao, Zhe Shao, Zhe Shao, Çağatay Iris, Bingjun Pan, Xiaonian Li , and Zhong-Ting Hu. "A review of China's municipal solid waste (MSW) and comparison with international regions: Management and technologies in treatment and resource utilization." *Journal of Cleaner Production* 293 (2021): 126144. https://doi.org/10.1016/j.jclepro.2021.126144

[92] Ngeno, Emily Chelangat, Kinyua E. Mbuci, Mohamed Chaker Necibi, Victor Odhiambo Shikuku, Chijioke Olisah, Roselyn Ongulu, Henry Matovu, Patrick Ssebugere, Almotasembellah Abushaban, and Mika Sillanpää. "Sustainable re-utilization of waste materials as adsorbents for water and wastewater treatment in Africa: Recent studies, research gaps, and way forward for emerging economies." *Environmental Advances* 9 (2022): 100282. https://doi.org/10.1016/j.envadv.2022.100282

[93] Gollakota, Anjani RK, Sneha Gautam, and Chi-Min Shu. "Inconsistencies of e-waste management in developing nations–Facts and plausible solutions." *Journal of Environmental Management* 261 (2020): 110234. https://doi.org/10.1016/j.jenvman.2020.110234

[94] Irunde, Regina, Julian Ijumulana, Fanuel Ligate, Jyoti Prakash Maity, Arslan Ahmad, Joseph Mtamba, Felix Mtalo, and Prosun Bhattacharya. "Arsenic in Africa: potential sources, spatial variability, and the state of the art for arsenic removal using locally available materials." *Groundwater for Sustainable Development* 18 (2022): 100746. https://doi.org/10.1016/j.gsd.2022.100746

[95] Njewa, Joel B., and Victor O. Shikuku. "Recent advances and issues in the application of activated carbon for water treatment in Africa: a systematic review (2007–2022)." *Applied Surface Science Advances* 18 (2023): 100501. https://doi.org/10.1016/j.apsadv.2023.100501

[96] Onigemo, M. T., A. A. Balogun, L. U. Odeh, E. A. Udoh, A. Mohammed, A. R. Omolusi, N. O. Ankomah, S. B. Akyea-Mensah, E. J. Onele, and M. D. Akoh. "Production and characterization of activated carbon from coconut shell for adsorption of lead (ii) ion from waste water." *Advanced Journal of Chemist, Section B: Natural Products Medical Chemistry* 6 (2024): 269-283. https://doi.org/10.48309/AJCB.2024.472061.1240

[97] Tayel, Ahmed A., Nancy A. Elsayes, Mohamed M. Zayed, Mohammed A. Alsieni, Fuad A. Alatawi, Adel I. Alalawy, and Amany M. Diab. "Powerful antibacterial nanocomposites from Corallina officinalis-mediated nanometals and chitosan nanoparticles against fish-borne pathogens." *Green Processing and Synthesis* 12, no. 1 (2023): 20230042. https://doi.org/10.1515/gps-2023-0042

[98] Burrows, Felicity, Clifford Louime, Michael Abazinge, and Oghenekome Onokpise. "Extraction and evaluation of chitosan from crab exoskeleton as a seed fungicide and plant growth enhancer." *Am. Eurasian J. Agric. Environ. Sci* 2, no. 2 (2007): 103-111.

[99] Putri, Devi Indrasari Mustopa, Handoko Darmokoesoemo, Ganden Supriyanto, Bernadeta Ayu Widyaningrum, and Heri Septya Kusuma. "Removal of Cd (II) from aqueous solution using biosorbent based on agricultural waste

sorgum bagasse (Sorghum bicolor (L.) Moench) activated NaOH." *Chemistry and Ecology* 40, no. 9 (2024): 1028-1054. https://doi.org/10.1080/02757540.2024.2376044

[100] Sulyman, Mohamed. "Agricultural by-products/waste as dye and metal ions adsorbents: A review." *Int. J. Eng. Sci* 6 (2016): 1-20.

[101] Bakar, Padilah Abu, Fatin Hana Naning, and Tasiu Zangina. "Electrical Responses of Chitosan-based Biosensor Toward Cadmium Ions Adsorption." *Semarak International Journal of Electronic System Engineering* 1, no. 1 (2024): 26-34. https://doi.org/10.37934/sijese.1.1.2634

[102] Sulistiyo, Carlos David, Kuan-Chen Cheng, Henoch Jaya Su'andi, Maria Yuliana, Chang-Wei Hsieh, Suryadi Ismadji, Artik Elisa Angkawijaya, Alchris Woo Goj, Hsien Yi Hsu, Phuong Lan Tran-Nguyen, and Shella Permatasari Santoso. "Removal of hexavalent chromium using durian in the form of rind, cellulose, and activated carbon: comparison on adsorption performance and economic evaluation." *Journal of Cleaner Production* 380 (2022): 135010. https://doi.org/10.1016/j.jclepro.2022.135010

[103] Darmansyah, Darmansyah, Sheng-Jie You, and Ya-Fen Wang. "Advancements of coal fly ash and its prospective implications for sustainable materials in Southeast Asian countries: A review." *Renewable and Sustainable Energy Reviews* 188 (2023): 113895. https://doi.org/10.1016/j.rser.2023.113895

[104] Pode, Ramchandra. "Potential applications of rice husk ash waste from rice husk biomass power plant." *Renewable and Sustainable Energy Reviews* 53 (2016): 1468-1485. https://doi.org/10.1016/j.rser.2015.09.051

[105] Gupta, Nishesh Kumar, and Anjali Gupta. "2D and 3D carbon-based adsorbents for an efficient removal of HgII ions: A review." *FlatChem* 11 (2018): 1-14. https://doi.org/10.1016/j.flatc.2018.11.002

[106] Chinedu, Ayodele. "Role of surface functional groups on the adsorption capacity of carbon nanomaterials in Nigeria." *Journal of Chemistry* 3, no. 1 (2024): 1-11. https://doi.org/10.47672/jchem.1972

[107] Park, Seri, Jeong-In Lee, Choon-Ki Na, Daegi Kim, Jae-Jin Kim, and Do-Yong Kim. "Evaluation of the adsorption performance and thermal treatment-associated regeneration of adsorbents for formaldehyde removal." *Journal of the Air & Waste Management Association* 74, no. 2 (2024): 131-144. https://doi.org/10.1080/10962247.2023.2292205

[108] Howarth, Ashlee J., Aaron W. Peters, Nicolaas A. Vermeulen, Timothy C. Wang, Joseph T. Hupp, and Omar K. Farha. "Best practices for the synthesis, activation, and characterization of metal–organic frameworks." *Chemistry of Materials* 29, no. 1 (2017): 26-39. https://doi.org/10.1021/acs.chemmater.6b02626

[109] Kornienko, Nikolay, Yingbo Zhao, Christopher S. Kley, Chenhui Zhu, Dohyung Kim, Song Lin, Christopher J. Chang, Omar M. Yaghi, and Peidong Yang. "Metal–organic frameworks for electrocatalytic reduction of carbon dioxide." *Journal of the American Chemical Society* 137, no. 44 (2015): 14129-14135. https://doi.org/10.1021/jacs.5b08212

[110] Carlsson, Håkan, Ulrika Nilsson, and Conny Östman. "Video display units: an emission source of the contact allergenic flame retardant triphenyl phosphate in the indoor environment." *Environmental Science & Technology* 34, no. 18 (2000): 3885-3889. https://doi.org/10.1021/es990768n

[111] Gillingham, Max D., Rachel L. Gomes, Rebecca Ferrari, and Helen M. West. "Sorption, separation and recycling of ammonium in agricultural soils: A viable application for magnetic biochar?." *Science of the Total Environment* 812 (2022): 151440. https://doi.org/10.1016/j.scitotenv.2021.151440

[112] Garmo, Øyvind A., Brit Lisa Skjelkvåle, Heleen A. De Wit, Luca Colombo, Chris Curtis, Jens Fölster, Andreas Hoffmann, Jakub Hruška, Tore Høgåsen, Dean S. Jeffries, W. Bill Keller, Pavel Krám, Vladimir Majer, Don T. Monteith, Andrew M. Paterson, Michela Rogora, Dorota Rzychon, Sandra Steingruber, John L. Stoddard, Jussi Vuorenmaa, and Adam Worsztynowicz. "Trends in surface water chemistry in acidified areas in Europe and North America from 1990 to 2008." Water, *Air, & Soil Pollution* 225 (2014): 1-14. https://doi.org/10.1007/s11270-014-1880-6

[113] Borgohain, Dhruba Jyoti, Mohammad Nazim, and Manoj Kumar Verma. "Cluster analysis and network visualization of research in mucormycosis: a scientometric mapping of the global publications from 2011 to 2020." *Library Hi Tech* 42, no. 1 (2024): 54-78. https://doi.org/10.1108/LHT-04-2022-0171

[114] Wahyuni, Sri, Satriya Pranata, Wawan Kurniawan, Rahayu Setyowati, Heni Heni, Arni Wianti, Aat Agustini, and Hera Hijriani. "Discovering the impact of bullying on adolescents through bibliometric analysis." *Scripta Medica* 55, no. 2 (2024): 219-229. https://doi.org/10.5937/scriptamed55-47959